Oceanus

REPORTS ON RESEARCH AT THE WOODS HOLE OCEANOGRAPHIC INSTITUTION

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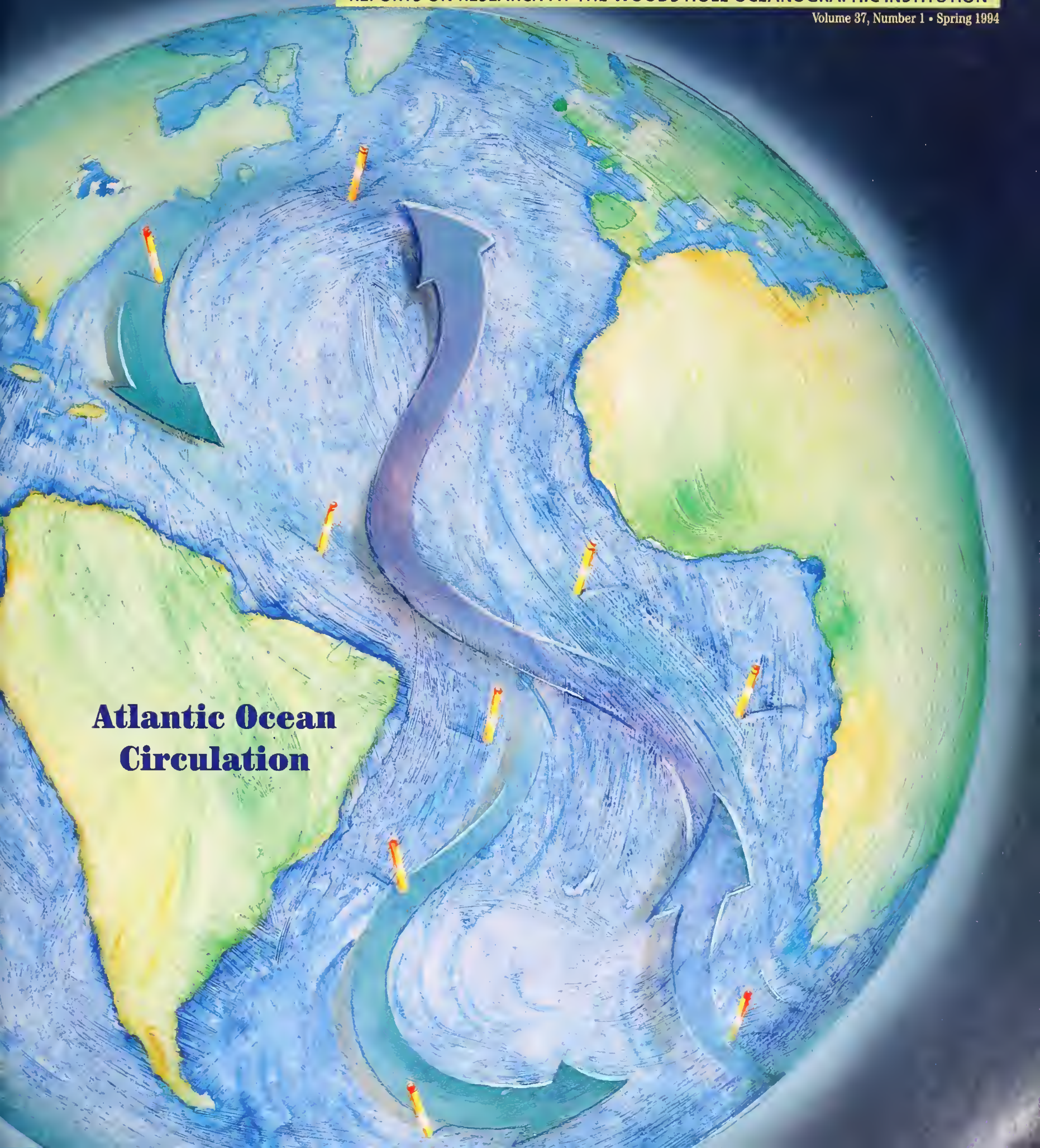

Atlantic Ocean Circulation

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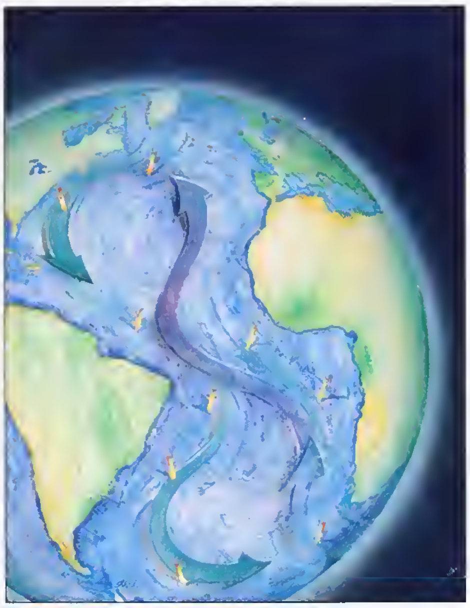

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Atlantic Ocean Circulation

WOODS HOLE OCEANOGRAPHIC INSTITUTION 1930

Editor: Vicky Cullen • Designer: Jim Canavan

Woods Hole Oceanographic Institution

Athanasius Kircher's seventeenth century view of Atlantic Ocean circulation.

The Atlantic Ocean

Progress in Describing and Interpreting Its Circulation

Who was the first physical oceanographer, the first to observe and ponder the cause of ocean movements? The answer is lost in history, of course, but the first writings on the subject date to early Greek civilization. By mid seventeenth century, expanding exploration of the New World had yielded enough geographic information to allow the Jesuit priest Athanasius Kircher to construct a chart of the world as well as detailed renditions of smaller regions, such as the Atlantic sector from his hand on this page. Much on this chart is recognizable today, both in regard to principal land masses and aspects of surface currents.

These charts include the first interpretations of the world oceans' vast subtropical gyres. However, the ocean circulation was deduced from extremely sparse data (nonexistent data in many regions). The voids were filled in with considerable imagination, an imagination almost completely unconstrained by physical principals, as physicists had not yet focused on the ocean. For example, Kircher was unaware of the physical impossibility of two currents, like those diagrammed east of Brazil, passing through one another, and he was particularly fond of the notion that subterranean passages linked maelstroms and currents, dispersing their entrances all over the world's oceans.

The classic era of physical oceanography began about 200 years later with recognition of the central


BOB MUNNS

Henry Stommel, Atlantis II, *1963*


WHOI ARCHIVES

John Swallow, Erika Dan, *1962*


WHOI ARCHIVES

Val Worthington, Atlantis, *1948*

role Earth's rotation plays in the physics of ocean motion and the fielding of expeditions for the explicit purpose of exploring ocean circulation. In a 1954 pamplet entitled "Why do our ideas about the ocean circulation have such a peculiarly dream like quality," Henry Stommel described this classic era of physical oceanography :

"(1) a grand cruise, or expedition, brings back many hydrographic stations' worth of data;
(2) extensive plots, graphs, and tabulations of the data are made and published for the benefit of future generations;
(3) certain of the more striking features of the data plots are noted;
(4) some plausible hypotheses are advanced to explain them.

This procedure usually exhausted the energy of those involved, and almost always the funds, and the study usually stopped at this stage."

However, the real focus of Stommel's pamphlet was a call to the research community for a fifth step:

"All of these steps are absolutely necessary, of course; otherwise we would know nothing at all about the ocean as it really is. But for the full development of the science there must be one additional step:
(5) the plausible hypotheses must be tested by specially designed observations. In this way theories can be rejected or accepted, or may be modified to become acceptable."

Shortly thereafter Stommel provided a prototype for this modern era of physical oceanography by hypothesizing on theoretical grounds the nature of the basic structure of the abyssal circulation. The hypothesis was almost immediately validated by the direct measurement program of John Swallow (the recipient early in 1994 of WHOI's first Henry Stommel Medal in Oceanography) and Val Worthington (WHOI Physical Oceanography Department Chairman from 1974 to1981).

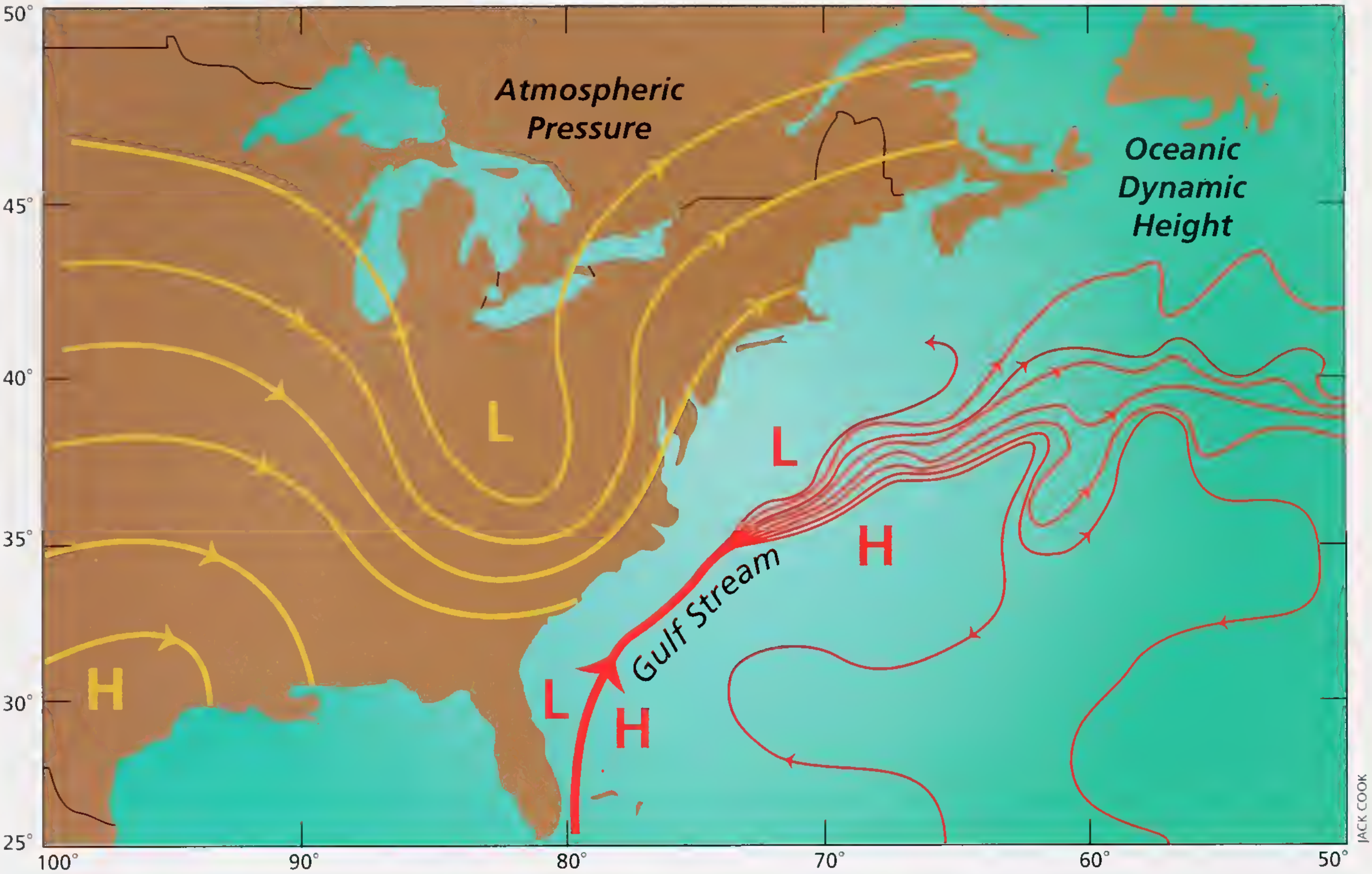
It is now about 37 years since Stommel published his pamphlet, and we can happily report much progress toward fulfilling his model for modern physical oceanographic research. We still feel very much like explorers when we carry out our measurement programs, but we conduct and interpret them within a framework of increasingly sophisticated physical understanding.

We initially planned this collection of reports on current research to focus on Atlantic deep circulation. The diversity of topics we ended up with is an indication of two aspects of the basic nonlinearity of physical oceanography. First is the high degree of linkage among physical phenomena: As some particular phemenon is examined, its physics often turns out to be directly linked to that of other phenomena. Second is the significant linkage among the scientists themselves: Because ocean physics is nonlinear, it is nearly impossible to be a specialist using a narrowly defined technique or working on a narrowly defined topic. We don't have to be experts in everything, but we do need a good understanding of a broad spectrum of phenomena that modify the physics of the ones we want to understand.

The WHOI Physical Oceanography Department has a 32-member scientific staff working with 6 postdoctoral associates, a 25-member technical staff, and 34 graduate students working on Ph.D.s, all ably supported by 36 assistants. The staff works on physical oceanographic problems throughout the world's oceans, spanning the full range of scales from millimeters to megameters, and utilizing a wide range of techniques from intensive field-measurement programs to equally intensive theoretical and numerical modeling studies. It is the largest concentration of physical oceanographers in the world. Seven of these scientists have contributed reports on one each of their many individual projects. They include a study of how two currents cross—not through each other, as in Kircher's drawing, but one beneath the other. One report deals with the very real complexity of the currents east of Brazil, and the rest with the actual "plumbing" of the deep circulation, not Kircher's subterranean passages, but instead an intricate system of abyssal circulation pathways by which waters sink from discrete source regions and move through the Atlantic Ocean.

Michael S. McCartney
Senior Scientist
Physical Oceanography Department

Editor's note: There are many references in this volume to the work of Henry Stommel, a physical oceanographer extraordinaire, who died in January 1992 at 71, a loss deeply felt by his colleagues both at WHOI and throughout the world. A special issue of *Oceanus* entitled *A Tribute to Henry Stommel* was published by the Institution in 1992. The inside back cover of this issue features the awarding of the first medal in his name.



Note the similarity of these imagined circulation fields for the atmosphere and ocean. Atmospheric pressure contours show a low over Canada and a high over southeastern United States. Arrows indicate direction of flow deduced from the geostrophic relation (that between horizontal pressure variations and horizontal currents), with higher speeds where the contours are closer together. Contour lines in the western North Atlantic illustrate an analogous field, the dynamic height at the sea surface. The compressed bundle emerging from the south off the coast of Florida is the Florida Current, which initiates the Gulf Stream system. The ocean surface is about a meter higher in mid basin than it is inshore of the Gulf Stream, and this drives the flow, indicated by arrows. Contours that peel off to the south indicate a partial clockwise circulation pattern around the high-elevation region, analogous to the clockwise flow around high pressures in the atmosphere.

A Primer on Ocean Currents

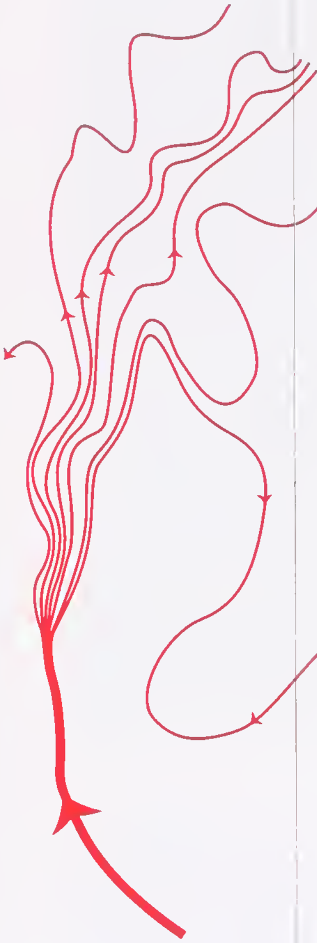
Measurements and Lingo of Physical Oceanographers

Volumes of Water Moving in Currents

Oceanographers express current flow in "millions of cubic meters per second," a term difficult for most people to comprehend. A large current, such as the Gulf Stream south of Nova Scotia, transports more than 150 million cubic meters per second, and typical transports for the smaller deep western boundary currents are 10 to 20 million cubic meters per second. Various dense overflows from marginal seas such as the Mediterranean are even smaller, 1 to 3 million cubic meters per second. For comparison, the sum of all the rivers flowing into the Atlantic is about 0.6 million cubic meters per second. The Amazon contributes about a third of that total, while the Mississippi River, whose rampages plagued the midwest last summer, accounts for only about 0.02 million cubic meters per second, roughly one ten-thousandth of the Gulf Stream's transport!

Properties of Seawater

Salinity: Though seawater's salinity is expressed in grams of dissolved solids per kilogram of seawater, today's methods measure seawater's electrical conductivity and then employ a well-known conversion algorithm to determine salinity. While coastal waters can exhibit a wide range of salinity as a result of freshwater runoff, most of the world ocean lies in the narrow salinity range 33.8 to 36.8.



Temperature: Oceanographers commonly refer to the "potential" temperature of a parcel of water. This recognizes that a parcel of water sinking from a surface source will, if it does not mix or exchange heat with surrounding waters, become slightly warmer as the pressure on it increases with depth. For example, if a parcel of surface seawater starts with a temperature of 0°C and salinity 35 and descends to 3,000 meters as part of an overflow, it may warm as much as 0.3°C. An instrument lowered into this overflow would sense this warmer temperature, which is called the "in situ" temperature. However, for most calculations and analyses oceanographers use the potential temperature, which corrects for this effect of pressure and thus remains 0.0°C.

The North Atlantic is the warmest and most saline of the world's oceans, having a mean potential temperature of 5.08°C and mean salinity of 35.09, compared to the global average of 3.51°C and salinity of 34.72. Most of the warmer and more saline waters of the world are concentrated in the upper kilometer of the subtropical and tropical circulation regimes in what is called the main thermocline (a region of rapid decrease in temperature with depth, in the North Atlantic typically the upper kilometer). About 77 percent of world-ocean volume is colder than 4°C, with salinities in the relatively narrow range 34.1 to 35.1. At the sea surface, only about 26 percent of the surface area is colder than 4°C, and it is within this area that the large volume of cold water acquires its characteristics before sinking and traveling along paths like those discussed in this publication.

Water Masses

The large volume of cold water described above comprises the "deep" and "bottom" waters. In the Atlantic there are several sources for these waters in both hemispheres. Each hemisphere's sources are blended by circulation and mixing. The net effect of northern sources dominates the deep water, while the net effect of southern sources dominates the bottom water. In regions where the two water masses coexist, the bottom water lies beneath the deep water, although because of their mixing there is no sharp demarcation between the two water masses away from their sources. Oceanographers often recognize these dominant sources through the proper names North Atlantic Deep Water and Antarctic Bottom Water. The Mediterranean outflow descends through the thermocline to form a mid-depth saline "tongue" of Mediterranean Water, which mixes downward through the uppermost part of the North Atlantic Deep Water. (Authors Bower and Price discuss the Mediterranean outflow.) Other sources for this uppermost part of the North Atlantic Deep Water are found in the Labrador Sea, where winter cooling produces a large volume of water at potential temperatures between 3.0°C and 4.5°C. Even colder waters are produced in the Nordic Seas (Greenland and Norwegian seas), the major source for the rest of the North Atlantic Deep Water. The Nordic Seas' sources are confined by the ridge system that connects Iceland to Greenland and Europe, but spill over the ridge to form dense overflows. The last source for the North Atlantic Deep Water is the Antarctic Bottom Water: Some of this water flows from the Brazil Basin in the South Atlantic across the equator into the North Atlantic (see articles by Hogg and Spall), where its ultimate fate is to upwell into the lower part of the North Atlantic Deep Water (see Pickart's article). Major currents like the Gulf Stream, and eddies like the North Brazil Current retroflection eddies (see Richardson's article), may penetrate the deep water and mix or disrupt the deep-current flow.

Current Velocity Measurements

Oceanographers measure current speed in two ways. For *direct measurements*, moored current meters record the speed of water flowing past them at intervals of hours or days, and surface or subsurface drifters reveal the pathways of the parcels of water in which they were launched. *Indirect estimates* use a relation between horizontal pressure variations and horizontal currents (called the geostrophic relation). This is analogous to a meteorologist's use of atmospheric pressure charts to deduce the wind field. In both cases the geostrophic velocity (of the wind or the ocean current) is parallel to the pressure contours on the chart and inversely proportional to the contour spacing. For the ocean, the pressure is determined from the field of density as deduced from an equation of state that links density to the actual measurements of temperature and salinity. However, this calculation in the ocean yields the velocity *difference* between the depth of the calculation and a "reference level." To convert this velocity difference to the absolute velocity, the reference level velocity must be determined by direct measurement, estimation, or some other means. Since the number of direct velocity measurements is generally very small relative to the hydrographic database available for application of the geostrophic relation, more often than not the "other means" are needed. These include:

- "Budgets," where a reference-level velocity is deduced by the requirement that the the sum of all the flows into and out of a region must be zero (since sea level isn't changing).
- "Water-mass analysis," where water-mass distribution suggests flow pattern velocities. (For example, a given source region may cause a property "tongue" along which the source's characteristic properties propagate and then mix with the surrounding water. This may show the flow direction and allow estimation of a speed.)
- "Level of no motion inference," where a zone of zero speed is assumed to lie between two zones of water flowing in opposite directions.

TOM KLEINDINST

Mike McCartney adjusts a conductivity/temperature/depth water sampling rosette.

Towards a Model of Atlantic Ocean Circulation

The Plumbing of the Climate's Radiator

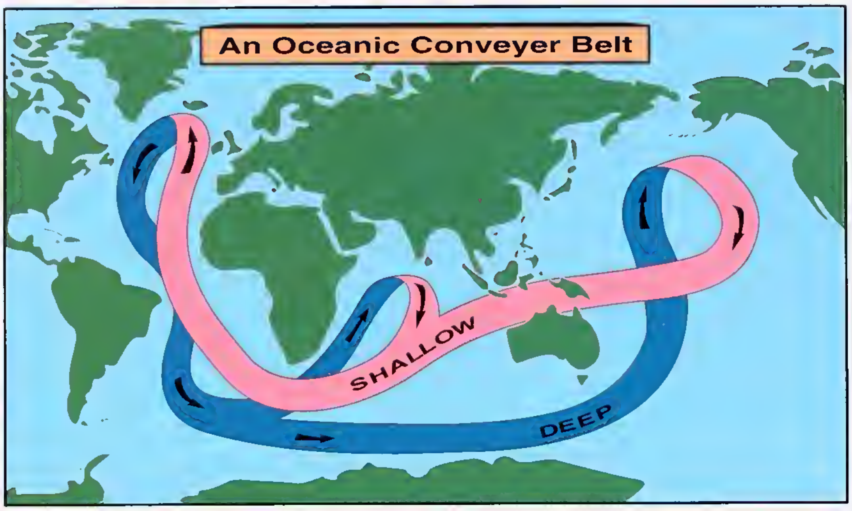
Michael S. McCartney
Senior Scientist, Physical Oceanography Department

The theme of physical oceanographers' research is the exploration and explanation of ocean circulation as a natural physical phenomenon with scales from millimeters to megameters. In this context, the word "model" usually brings to mind a theoretician analytically or numerically solving some system of equations that might capture the essence of the physics of some particular part of the ocean circulation. In other words, the theoretician's model attempts to explain the causes and mechanisms of observed phenomena in the ocean, or perhaps predict unobserved ones.

Those of us who make ocean circulation observations often get involved in a different sort of model. While in some sheer numerical sense there are a lot of ocean circulation measurements, the circulation is remarkably complex, so the measurements are actually rather sparse relative to what is needed to describe the phenomena unambiguously. Thus we also become modelers, for even a basic description of ocean circulation is a model: an attempt to provide in words and pictures a synthesis, or simplified interpretation, of the measurements.

One such model, the popular "conveyor belt" interpretation (overleaf), has emerged from the increasing focus (over roughly the last decade) on the ocean's role in global climate. Its underpinnings are, however, traced to some of the oldest observations and

The conveyor belt image of the Atlantic Ocean's role in exchanging warm and cold waters with the rest of the world's oceans. Developed by W. S. Broecker of the Columbia University's Lamont-Doherty Earth Observatory, it represents the Atlantic as a radiator that converts imported warm water to exported cold water. The intensity of the conversion rate is generally estimated at between 10 and 20 million cubic meters per second.



JAYNE DOUCETTE

their early interpretations as expressed by Benjamin Thompson, Count of Rumford, in 1797 and elaborated by William Carpenter and Joseph Prestwich in the 1870s. This very simple conveyor-belt model is based on a few fundamental circulation observations:

- Cold water with identifiable North Atlantic characteristics can be traced in diluted form through most of the world ocean.
- To conserve mass, an equal volume of warm water must replenish the cold water draining out of the North Atlantic.
- There is a large liberation of heat from the ocean to the atmosphere at middle and high North Atlantic latitudes.

The model, as far as it goes, is consistent with these observations. In particular, the estimated replenishment rate, the estimated intensity of heat loss, and the observed temperature change of the warm-to-cold conversions are in harmony.

An observationist builds on a simple model like the conveyor belt by checking its consistency with observations other than the ones on which it was based. The broader the base of such consistency, the more "real" the model is perceived to be, and the more valuable it becomes as a benchmark for testing a theoretician's model or as a guide for theoretical models—for example, what *is* the circulation that the model should duplicate? But when consistency with observations is lacking, the observationist must augment the simple model by building in missing pieces—or perhaps discard it as a flawed starting point.

The figure opposite is an example of an augmented version of part of the conveyor-belt model. WHOI Senior Scientist Bill Schmitz and I developed it over the last few years to describe the field of horizontal warm-water circulation in the North Atlantic (see publication footnote). Such circulation schematics attempt to integrate all relevant measurements and interpretations, in this case both our own and those of our many colleagues around the world, present and past. Such circulation schematics have an even longer history than the conveyor-belt interpretation, for we follow the footsteps of centuries of ocean explorers who have tried to make maps of Atlantic Ocean surface circulation. One of the oldest of these, by the Jesuit Athanasius Kircher, dates from 1678 (see page 1).

It is important to recognize two things about circulation schematics. First, they are almost instantly rendered obsolete by new measurements, for our science is still in a basic exploration phase. Second, they represent a subjective synthesis: Other oceanographers might emphasize different aspects, that is, draw the picture and estimate the transport amplitudes somewhat differently—the product is very much "in the eye of the beholder!"

The schematic opposite points out a problem inherent in the process of sorting out ocean circulation's role in climate. We show 13 million cubic meters per second of warm water entering the North Atlantic across the equator; this is our estimate of the magnitude of cold-water production in the North Atlantic and thus of the intensity of the conveyor belt. However, the Gulf Stream south of Nova Scotia transports about six times this amount! The "recirculating gyre" components of measured North Atlantic warm-water transport thus greatly exceed the amount that is estimated to convert from warm to cold. (The recirculating gyre can be seen in the figure opposite as the Gulf Stream water that moves across and down the middle of the Atlantic to rejoin the northward flowing currents.) Thus, the part of the circulation field most important for climate issues is a small fraction of the field actually being measured. The physical phenomenon responsible for the northward transport of warm water through the North Atlantic is a linked set of gyre flows rather than the simple image of the upper limb of the conveyor belt. The physics of the western intensification of these gyres was first deduced by Henry Stommel in 1948, and their relationship to the wind and thermal and hydrological forcing remains a very active research topic to this day. The synthesis of observations, their interpretation, and their physical modeling proceed in parallel.

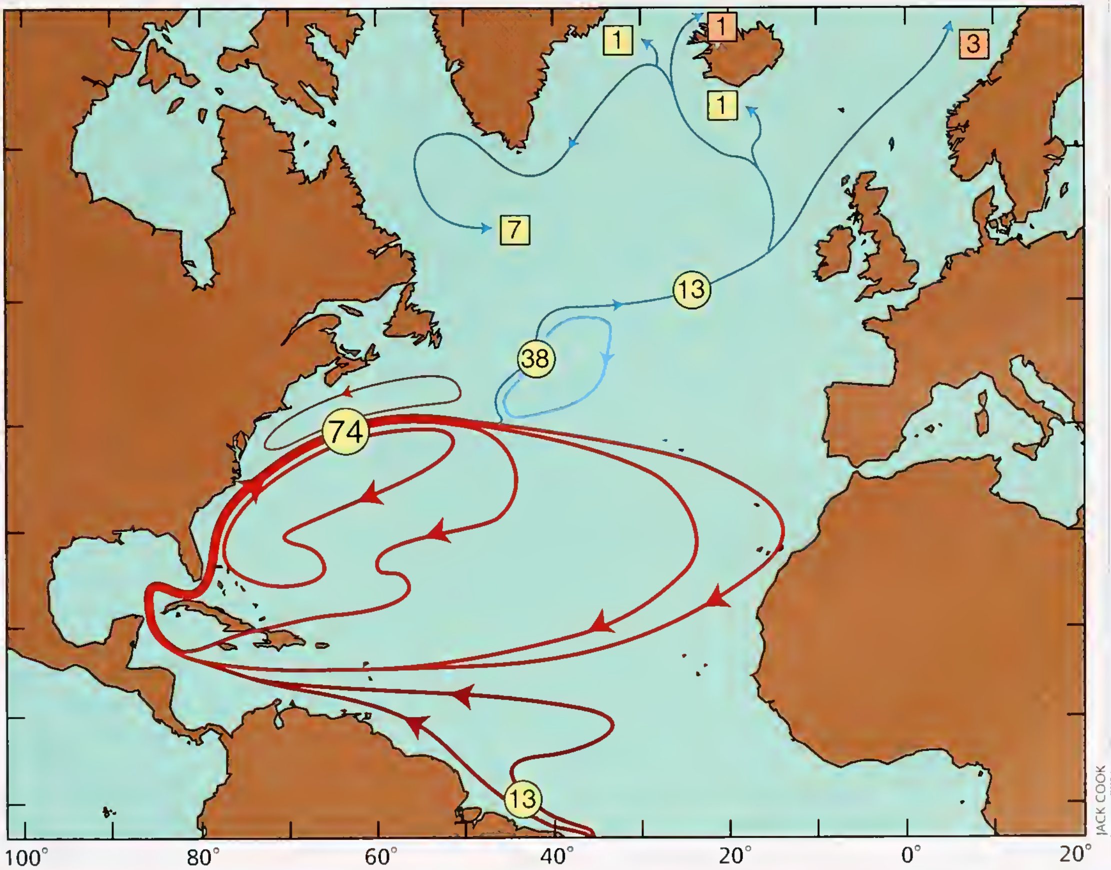
Similar degrees of complexity are emerging from studies of the cold-water part of the system, studies that illustrate the model-building process. The dominant components of the meridional flow of cold water are western intensified both within the Atlantic and within its subbasins, which are defined by abyssal ridges. In Kircher's old circulation-system map on page 1, water was imagined to descend into subterranean passages and to reemerge in faraway places. The real

plumbing of the system is internal to the ocean itself, but it achieves a similar result: Waters sink in a few places to mid-depth or the seafloor (but not with the violence of maelstroms!) and are carried by current systems to the far reaches of the world ocean by deep currents. The width of these currents is restricted by the internal physics of the ocean and steered by the abyssal topography (not subterranean passages!)

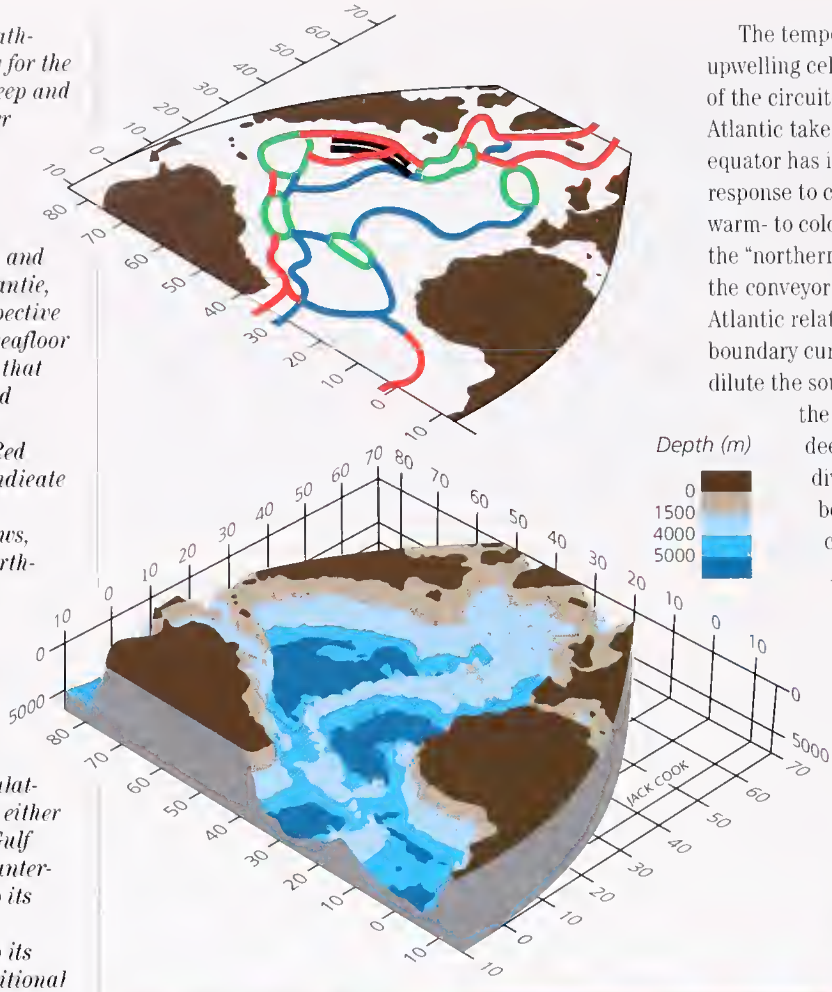
The physics of this deep western intensification was first elucidated by Henry Stommel in the mid 1950s (see page 22). Such intensified flows are "easier" to measure because they are geographically small. Measurements of the intensity of these southward flows show a magnitude often twice or more than that expected from the simple conveyor-belt intepretations. Flow measurements in the basins' interior regions have revealed that a gyre component is responsible for the larger-than-expected boundary current flows. This system of gyres is more broken up by abyssal bathymetry (top figure overleaf) than are the large warm-water gyres. This model preserves the intensity of the conveyor-belt conception's net meridional flows of cold water, but it is also consistent with measurements of the intensity of deep western boundary currents and interior flows. Combining this cold-water schematic with the warm-water circulation of the figure below gives a representation of the full three-dimensional ocean circulation that the quasi-two-dimensional conveyor belt simplifies. Perhaps it is more aptly described as a baggage carousel than a conveyor belt, with water parcels mostly going round and round rather than directly towards their destinations.

The latest work on the Atlantic circulation model involves the cold-water system near the equator. For this, MIT/WHOI Joint Program graduate student Marjy Friedrichs, Associate Scientist Mindy Hall, and I examined the southward cold-water transport in the tropics of the North and South Atlantic. We found the North Atlantic's transport dominated by a colder water mass than the South Atlantic's. The shift does not occur as a smooth north-to-south transition, for the contrast in the western basin persists even quite close to the equator. Measurements indicate that a zonal upwelling cell in the cold water along the equator achieves the transition (bottom figure overleaf).

One of the difficulties we face in interpreting our data is visualization of the three-dimensional structure of the circulation. In the top figure overleaf, the vertical structure of the deep circulation was averaged to focus on the overall horizontal flow. In the bottom figure, part of the vertical structure of that deep flow is shown in a perspective view, with the ocean above 2,000 meters removed, and with the view looking northwest towards the continental slope of Brazil from a point in the middle South Atlantic south of the equator. The result looks a bit like an expressway cloverleaf, but with no connections between the two levels. We believe that the indicated seven million cubic meters per second eastward flow of the colder level upwells in the eastern tropical Atlantic to supply the indicated seven million cubic meters per second of westward flowing water on the warmer level of the cloverleaf.



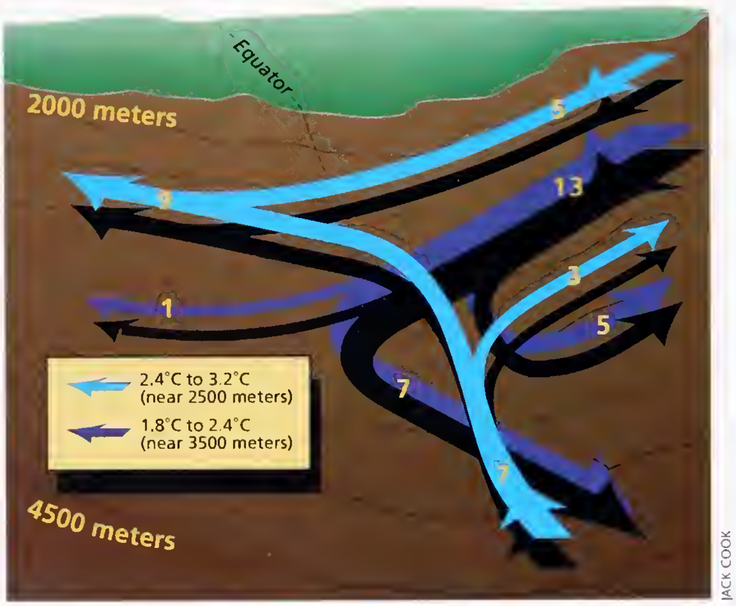
A simplified rendition of the system of linked recirculation gyres and flow pathways of imported warm water as it makes its way from the equator to the subpolar basins of the North Atlantic, with flow rates in millions of cubic meters per second, indicated by circled numbers. Partition of the 13 million cubic meters per second estimated net northward warm-water flow into distinct cold-water production regions is given by the numbers in squares: 7 million cubic meters per second sinking in the Labrador Sea, 4 million cubic meters per second (pink squares) entering the Nordic Seas to return as dense overflows into the region south of Iceland, and 2 million cubic meters per second entrained into these overflows.



Principal pathways of flow for the combined deep and bottom water (all water colder than 3°C) circulation in the North and tropical Atlantic, with a perspective view of the seafloor bathymetry that contains and shapes the pathways. Red pathways indicate southward trending flows, and blue northward. The parallel black strips are the axes of the intense deep recirculating gyres to either side of the Gulf Stream (counterclockwise to its north and clockwise to its south). Additional counterclockwise recirculating gyres are shown in green. These gyres mix the characteristics of the northward and southward flowing waters, and intensify the southward flow along the western boundary.

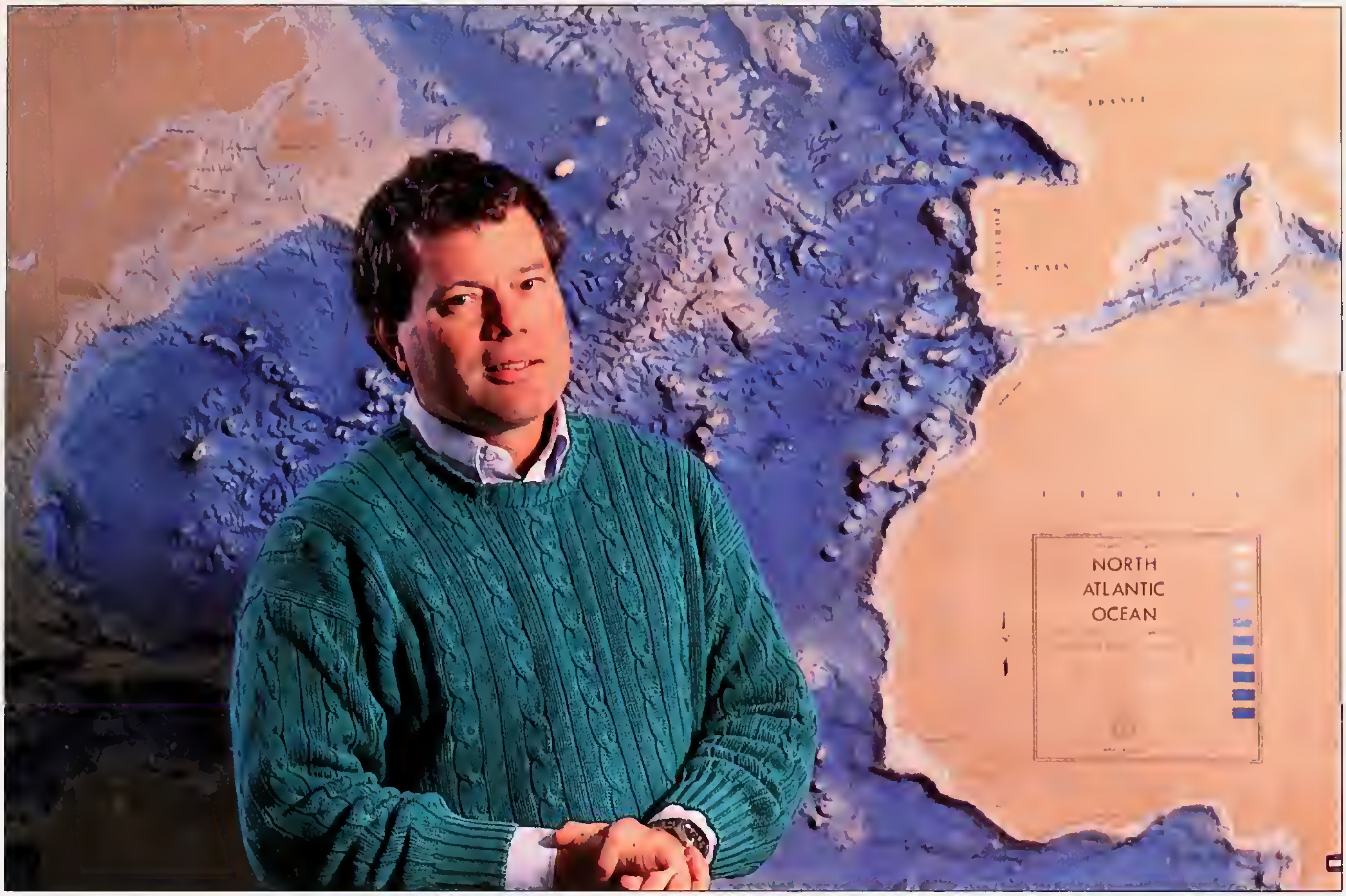
The temperature change involved in this equatorial upwelling cell, about 0.5°C, is small, but the recognition of the circuitous route that cold water from the North Atlantic takes in order to move southward across the equator has implications for the mode of the system's response to climate change. A perturbation in the warm- to cold-water conversion process that provides the "northern source" water to the cold-water limb of the conveyor belt does not simply move through the Atlantic relatively undiluted in a deep western boundary current "filament." The recirculation gyres dilute the source water's characteristics with those of the basin's interior water mass. The diluted deep water that reaches the equator is mostly diverted into the interior and further altered before returning to the western boundary to continue southward through the South Atlantic—where we are finding additional recirculation gyres. These new observations and interpretations present a new modeling challenge to the theoreticians, and, for we observationists, it points to new measurements that will improve our interpretive circulation model.

This work was supported by the Office of Naval Research, the National Science Foundation and the National Oceanographic and Atmospheric Administration. One of the most recent relevant publications on it is "North Atlantic Circulation" (W.J. Schmitz and M.S. McCartney, Reviews of Geophysics 31, *pages 29 to 49).*



An interpretation of tropical cold-water circulation in the Atlantic, looking northward from below the equator. Numbers indicate flow rates in millions of cubic meters per second. In the North Atlantic, a deep western boundary current is dominated by deep water near 2°C. This southward current mostly turns eastward, away from the continental slope, after crossing the equator, and is warmed by downward diffusion of heat in the equatorial zone, causing an "upwelling" into the warmer layer. Westward flow of this layer in the equatorial zone (dominated by deep water near 2.7°C) diverges near the western boundary into northward and southward flows, with the latter dominating the deep South Atlantic western boundary current.

Mike McCartney came to WHOI 20 years ago with degrees in theoretical fluid dynamics. Within two weeks of his arrival Fritz Fuglister, one of the real pioneers of Atlantic physical oceanography, took him to sea on the institution's research vessel *Chain*. It changed his outlook! Recently Mike added up his research cruise time and found that he has averaged a month per year, including eight crossings of the Atlantic. He says that the main change over the years is that the cruises come in clumps, for example none in 1993 and a scheduled 90 days in 1994 for crossings of the South Pacific and of the Antarctic Circumpolar Current. Between the cruises and the fun of untangling the data's message about the circulation and the physics, he further relaxes by taking long solo cruises on his old gaff cutter and untangling all her rigging. He doesn't understand why people think it odd that he spends so much time on the water.



TOM KLEINDINST

Jim Price discusses the Mediterranean overflow.

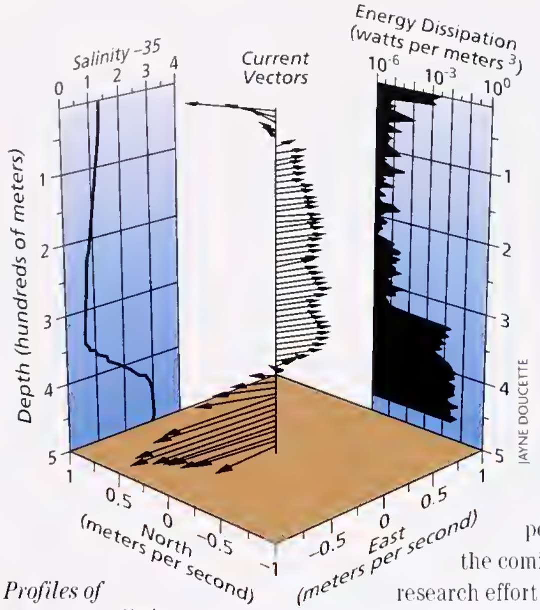
Dynamics and Modeling of Marginal Sea Outflows

Out They Go, Down, and Around the World

James F. Price
Associate Scientist, Physical Oceanography Department

The waters of the deep ocean carry a huge volume of heat and dissolved gases along paths that cross ocean basins and may encircle the globe. These paths all originate in one of a handful of polar marginal seas where cooling or evaporation makes water sufficiently dense that it can sink to great depths in the open ocean. The paths can be thought of as terminating where the deep water returns to the sea surface, usually after many centuries, and after being slowly modified by mixing with warmer waters and by a rain of organic material from the upper ocean. In special regions where deep water comes to the surface in greater volume, along the equator and in coastal upwelling zones, the resulting nutrient load of the deep water leads to the highest productivity found in the oceans. This global transport aspect of deep-ocean circulation has long been recognized as an important element of the ocean's geochemistry and has been studied intensively by oceanographers since at least the 1920s.

It is a sign of the times that we now also think of the deep ocean as a storage site, inadvertent or planned, for anthropogenic substances such as radioactive wastes and greenhouse gases including carbon dioxide and fluorocarbons. Most of these are harmful to the atmospheric environment, and some of these substances may also harm sea life. To evaluate the risks, we need to know with some confidence where and in what



Profiles of currents, salinity, and turbulent energy dissipation through the core of the Mediterranean outflow (which is the saline bottom layer approximately 100 meters thick). The Strait of Gibraltar is to the right, and the outflow current is moving southwest into the Gulf of Cadiz.

quantity these materials are injected into the deep sea, and where and when they will reappear at the sea surface. Our present knowledge of deep-ocean currents is elementary, and reliable estimates of deep-ocean transport and storage are very difficult to make. Research aimed at improved understanding of deep-ocean circulation is thus likely to be one of the focal points for oceanography in the coming decade. This research effort will go forward at many institutions using ideas and resources from many disciplines (see, for example, the 1992 Paleoceanography *Reports on Research*, page 11).

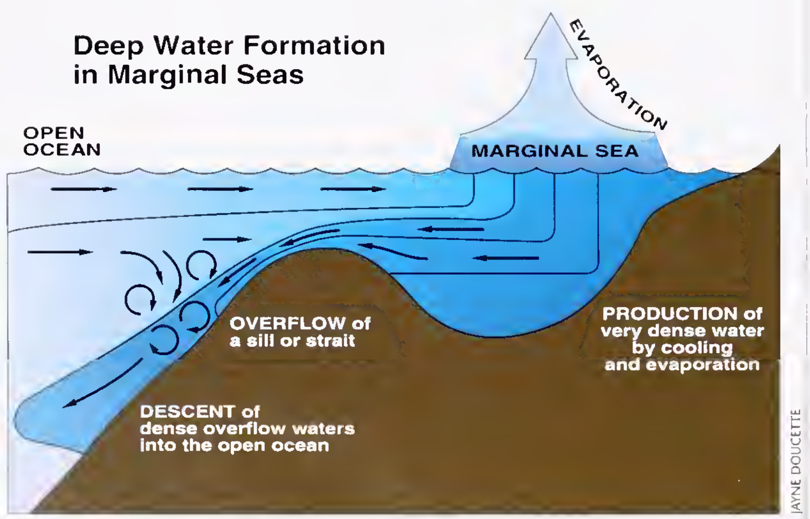
One intriguing aspect of deep circulation is the dynamics of the dense marginal-sea outflows that initiate deep circulation. It is tempting to say that these outflows "drive" the deep circulation, but the processes that cause the deep water to return to the surface are probably of equal importance in the long run. What we can say with some confidence is that the transport, temperature, and salinity of the outflow waters are crucial factors in setting the properties of the deep water, and they are clearly also crucial in the overall problem of understanding deep-water circulation.

The first important step in my research program to understand outflows was to make a detailed field survey of the Mediterranean outflow in the Gulf of Cadiz, in collaboration with Tom Sanford of the University of Washington and Rolf Lueck of the University of Victoria. We measured current profiles through the outflow and some properties of the turbulence as well (see figure at left). These data were analyzed by Molly O'Neil Baringer, then a Ph.D. student in the MIT/WHOI Joint Program, and by Greg Johnson, a recent WHOI graduate then at the University of Washington as a postdoctoral researcher. The data showed that the Mediterranean outflow begins with highly saline and very dense water and yet ends up making intermediate (rather than deep) water because it mixes intensely with oceanic water as it first begins to descend the continental slope in the Gulf of Cadiz (see figure below left). The large bottom slope combined with the large initial density causes a very strong buoyancy (gravitational) acceleration that increases the current speed to more than a meter per second. This strong current causes instability at the interface between the North Atlantic water and the Mediterranean water, which in turn causes mixing that dramatically reduces the salinity and density of this outflow.

The end result is that mixed Mediterranean Water settles into the North Atlantic thermocline at a depth of about 1,000 meters. Mixing (or entrainment) causes the transport to increase from about .7 million cubic meters per second at the Strait of Gibraltar to about 2.5 million cubic meters per second in the North Atlantic. The mixed Mediterranean water makes an important salinity anomaly that spreads across the North Atlantic basin (see Amy Bower's article on page 12).

A study of historic data on the subpolar outflows (two flow from the Norwegian and Greenland seas and one from the Weddell Sea) showed a similar pattern of strong mixing as these outflows began to descend the continental slope. However, these subpolar outflows all produce bottom water despite beginning with a lesser density than does the Mediterranean outflow. Why the difference?

To understand outflow mixing in a quantitative and ultimately predictive way, Baringer and I developed a numerical model that simulates a single outflow descending into a resting ocean. The elements of the model dynamics were known from the field study: We knew that topographic and Coriolis accelerations (an effect of Earth's rotation that accelerates moving ocean water to the right in the Northern Hemisphere and to the left in the Southern Hemisphere) were essential, and we had evidence that mixing occurred primarily in response to strong currents. These and other insights, when combined with the conservation laws for mass and momentum, led to a simple but somewhat realistic outflow model that we could use to interpret observations and explore outflow dynamics. The bottom figure opposite shows observed and simulated density and speed along the path of the Mediterranean outflow. The model has some skill at simulating this outflow, and it has proven useful for understanding the differences and similarities between this and the other major outflows.



A schematic showing three stages in the formation of deep water by a marginal sea. A shallow and confined marginal sea acts as a concentration basin that produces a comparatively small volume of very dense water. Before this dense water can settle into the open ocean it must descend the continental shelf and slope, and may mix significantly with oceanic waters along the way. The water that finally reaches the deep sea may be quite different from the water that first came out of the marginal sea.

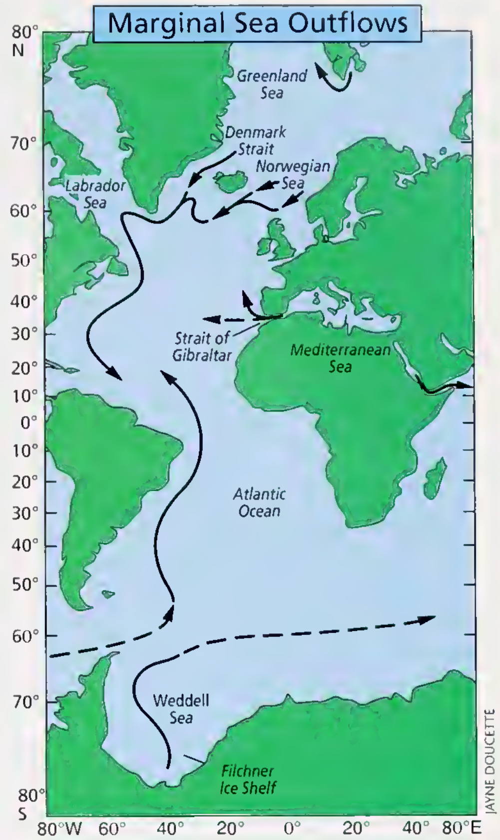
Experiments with the model gave some surprising results. The most important is the apparent high sensitivity of marginal-sea outflows to the properties of the oceanic water through which the outflow descends. If there is a large density contrast between the outflow and the oceanic water (as there is in the Mediterranean case because it enters the North Atlantic at a comparatively shallow depth, approximately 300 meters, before descending to about 1,000 meters), then the outflow current will accelerate to higher speeds, which causes more intense mixing and increased loss of density. Such an outflow is not likely to make bottom water, but it will acquire an enhanced transport that may exceed the initial transport by a factor of two or more. The subpolar outflows begin at a much greater depth, approximately 700 meters, and do not have such a large density difference with respect to the surrounding oceanic waters. While they too mix with the surrounding ocean waters, they nevertheless remain dense enough to reach the seafloor.

From this work it appears that to understand the product water of a marginal-sea outflow (and thus the properties and transport of the water injected into the deep-ocean circulation), we have to know the properties of the oceanic water through which the outflows descend. This is a reminder that the ocean circulation is a highly interconnected system; few components are truly independent of the others. Detailed studies of single components, in our case the outflows, are essential to make headway on such complex systems, but can yield only partial insight into the workings of the overall system.

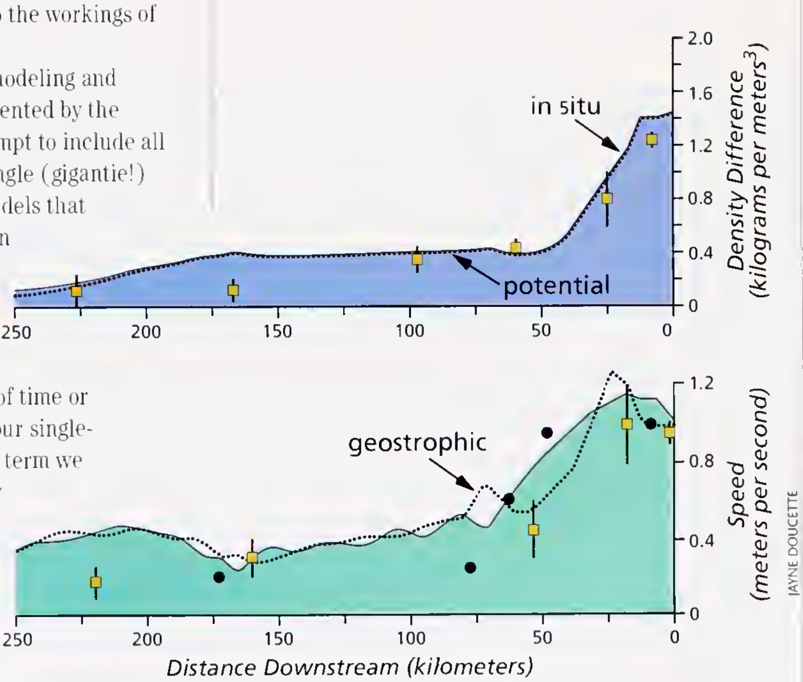
The other, holistic, approach to modeling and analyzing ocean circulation is represented by the general circulation models that attempt to include all or most circulation processes in a single (gigantic!) numerical calculation. It is these models that will yield the estimates of deep-ocean transport and storage needed to guide environmental policy. Because they are inclusive, these general circulation models must necessarily give up some resolution of time or space that we can easily achieve in our single-purpose outflow models. In the near term we will work on ways to include outflow models within the framework of the general circulation models. Our goal is to develop outflow models that are compatible with the lower resolution of the general circulation models, and yet remain responsive to changing bottom topography, sea level, or climate. Once we have done this, we can analyze the general circulation models to learn how and where materials are absorbed and transported by deep-ocean circulation, and perhaps learn where they may come to the surface again.

This work was funded by the Office of Naval Research. The Gulf of Cadiz results were described in "Mediterranean Outflow Mixing and Dynamics (Science, *26 February 1993, pages 1277-1282), and the modeling work is described in a paper scheduled for 1994 publication in* Progress in Oceanography.

Jim Price became interested in physical oceanography while studying plasma physics at the University of Miami. At WHOI he has worked on problems involving the upper ocean, and more recently the deep ocean circulation, and has been active in the MIT/WHOI Joint Program for graduate education. He has three teenaged children who can easily outrun him at any distance, but he remains about even in tennis, and claims to be vastly superior at cooking (anything spicey), painting (just fish), and tending the household pets (currently one rabbit).



Four major outflows feed dense water into the North Atlantic. The three subpolar outflows (through the Denmark Strait and from the Norwegian and Weddell seas) all produce bottom water, while the Mediterranean outflow produces intermediate water despite beginning as the densest water.



The observed (data points) and simulated (solid lines) speed and density along the path of the Mediterranean outflow. The simulated density shows a very rapid decrease where the outflow begins to descend the continental slope (about 30 kilometers downstream from the start). The profiles in the top figure opposite, made in this region, indicate very strong outflow currents and intense turbulence due to mixing.

TOM KLEINDINST

Amy Bower works with RAFOS floats.

Meddies, Eddies, Floats and Boats

How Do Mediterranean and Atlantic Waters Mix?

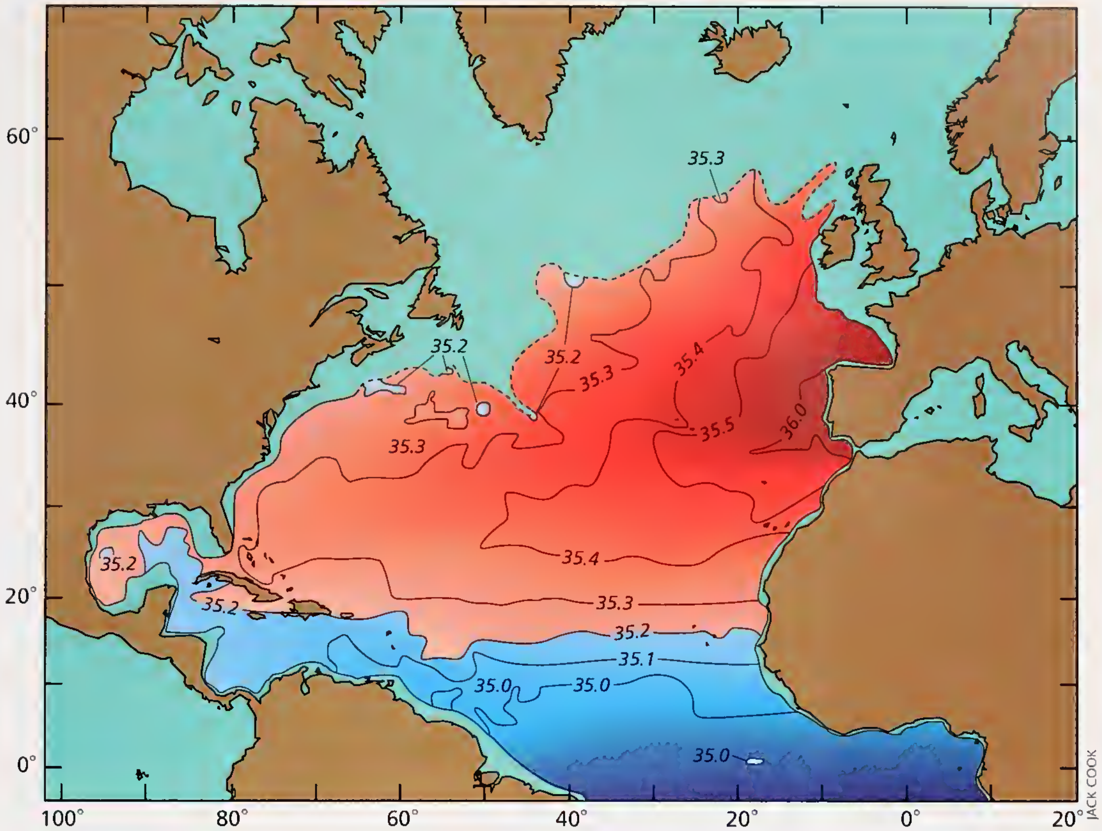
Amy S. Bower
Assistant Scientist, Physical Oceanography Department

One of the most prominent features of the North Atlantic Ocean is the tongue of salty water that extends from Portugal westward at mid depth. This tongue results from an exchange flow between the Mediterranean Sea and the Atlantic through the Strait of Gibraltar. Atlantic Water flows through the strait into the Mediterranean, where it is converted into saltier Mediterranean Water by an excess of evaporation over precipitation. Mediterranean Water, which is heavier than Atlantic Water due to its higher salt content, escapes into the North Atlantic through the strait under the incoming Atlantic Water. After leaving the strait, the dense Mediterranean Water sinks and turns to the right, following the continental slope of Spain and Portugal in a relatively narrow jet known as the Mediterranean Undercurrent. Eventually, the Mediterranean Water leaves the coast and spreads out into the North Atlantic to form the tongue of salty water shown in the top figure opposite.

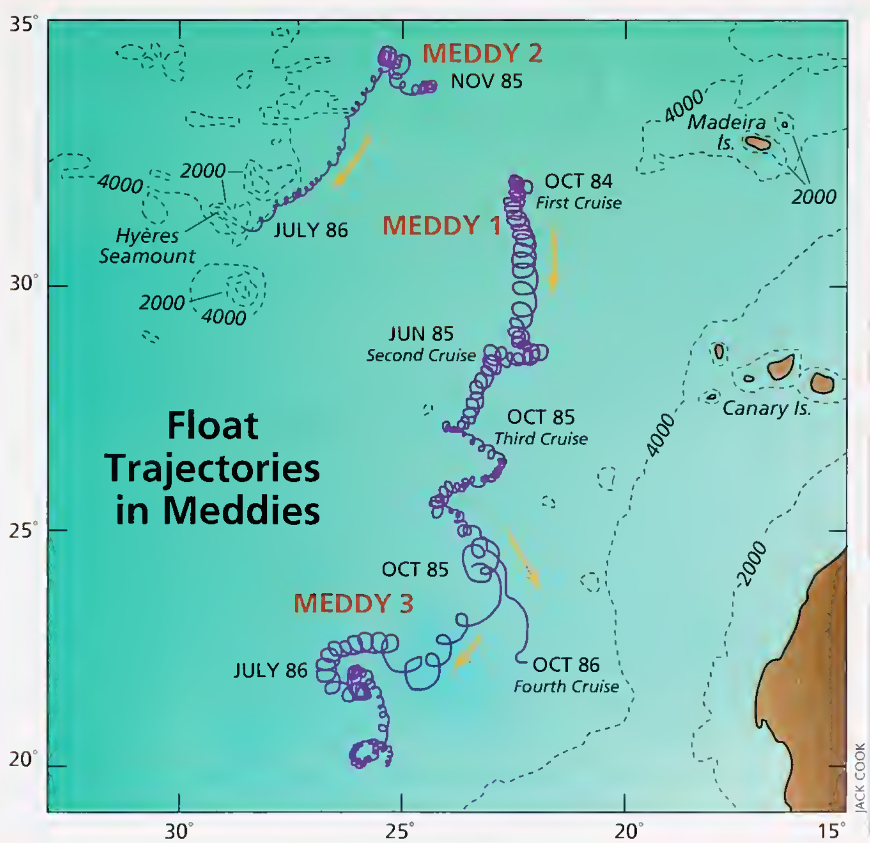
Traditionally, physical oceanographers have thought Mediterranean Water to be carried out into the North Atlantic by steady currents, and further dispersed by some random mixing. While these processes certainly contribute to the spreading of Mediterranean Water, the discovery of a new type of eddy in the Atlantic has forced us to revise our thinking about how Mediterranean Water is carried from its source. These eddies, found at about 1,000 meters, are rapidly rotating lenses that

contain a core of warm, highly saline Mediterranean Water. One of the earliest observations of such an eddy occurred in 1976 when researchers making temperature and salinity measurements near the Bahamas encountered a patch of unexpectedly warm and salty water. The water property characteristics of this patch or lens suggested it was of Mediterranean origin. An acoustically tracked float quickly deployed in the lens showed a persistent clockwise rotation.

This discovery prompted a more rigorous search for salty lenses in the eastern Atlantic, closer to the Mediterranean. In the last decade, many new lenses have been found and studied using hydrographic measurements, velocity profilers, and floats. Eastern Atlantic salt lenses, now known as "meddies," for *Med*iterranean edd*ies*, are typically 100 kilometers in diameter, centered at 1,000 meters, and extend over about 800 meters vertically. The water in the meddy cores is as much as 4°C warmer and 1 part per thousand more saline than the background fluid, indicating that meddies must form from Mediterranean Undercurrent water somewhere along the coast of Spain or Portugal. Due to their rapid rotation, mixing between the meddy cores and the surrounding fluid is limited. Thus meddies are capable of carrying the salty Mediterranean Water far from its source. This is illustrated in the figure at right, which shows the trajectories of three floats launched in eastern Atlantic meddies. When first identified, these meddies were probably already at least one year old, and had traveled over 1,000 kilometers from their formation site. Meddy 1 was tracked with floats for two years, and surveyed hydrographically four times. It traveled about 2,000 kilometers and decayed slowly over that time.



Salinity on the 10°C surface (about 1,000 meters deep) from a 1976 monograph by Valentine Worthington. The high-salinity water of Mediterranean origin is shown in shades of red.



Trajectories of three acoustically tracked floats deployed in meddies (Mediterranean eddies). The rapid clockwise looping of the floats is characteristic of meddies. (Courtesy of Philip Richardson)

John Kemp prepares to deploy a sound-source mooring aboard R/V Oceanus *in May 1993. This and other sound sources are used to track RAFOS floats.*

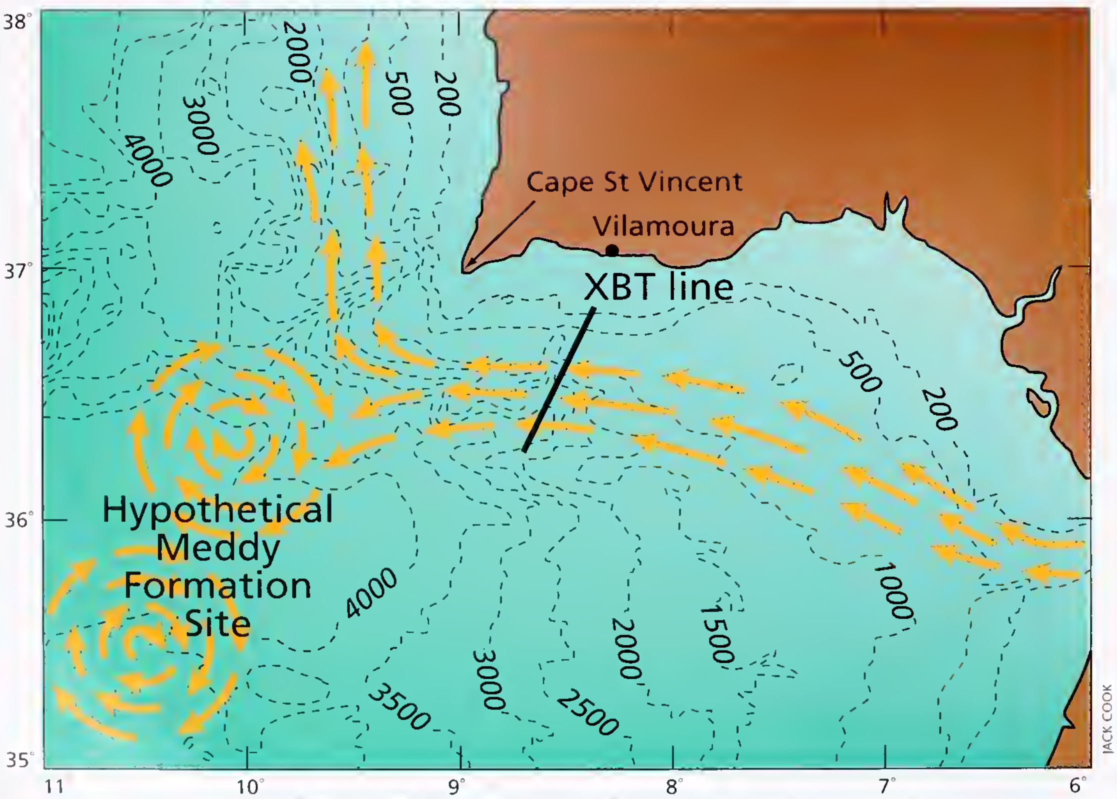
slowly over that time. Meddy 2, on the other hand, dispersed its salty core catastrophically when it collided with a seamount.

Although the general characteristics of meddies have been well-documented, fundamental questions about their formation remain. For example, where do meddies form? What physical process is responsible for their formation? How many meddies are born each year, and how long does it take a meddy to come to life? Since meddies play a significant role in carrying salty water from the Mediterranean into the Atlantic, we must learn more about their life histories if we are to understand how the distributions of temperature and salinity are maintained in the North Atlantic.

A new program, called A Mediterranean Undercurrent Seeding Experiment (AMUSE), is currently underway to address these questions. This study is being conducted jointly with Laurence Armi of Scripps Institution of Oceanography, and Isabel Ambar of the University of Lisbon. In this experiment, 40 subsurface RAFOS floats are being launched in the Mediterranean Undercurrent south of Portugal over a six-month period, at the rate of two per week. They are being tracked acoustically using an array of German, French, and US sound beacons moored in the eastern North Atlantic. (RAFOS is the reverse spelling of the acronym SOFAR, for SOund Fixing And Ranging, and refers to the fact that RAFOS floats listen for sound signals transmitted by moored sound sources, rather than themselves transmitting to moored listening stations, as SOFAR floats do.)

The floats will remain underwater for about one year, following the movement of Mediterranean Water as it leaves the coast and mixes into the Atlantic. Some floats will most likely be trapped in newly formed meddies (see schematic below). At the end of their mission, each float will automatically drop a ballast weight, rise to the surface, and transmit its stored acoustic tracking data, as well as temperature and pressure data, by radio signals to receivers on two satellites maintained by the French-run Service ARGOS. The data will then be sent automatically over the Internet network to computers at WHOI. The floats themselves are considered expendable, though we have recovered a few test floats that were set to surface after a month.

It would be impractical, costly, and unnecessary to retain a large oceanographic research vessel for the float deployments. Just 2 meters long and weighing only about 10 kilograms, the floats, which look like giant test tubes, can easily be lifted and dropped over the side by one or two people. Vertical temperature profiles are necessary to locate the float launch

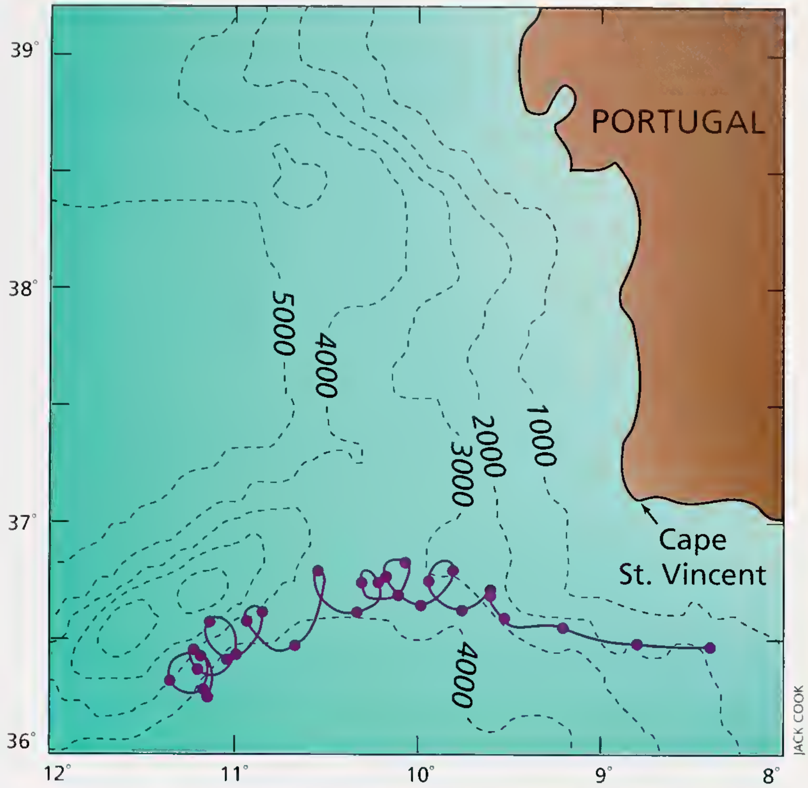


A schematic diagram showing the Mediterranean Undercurrent (arrows) and the expendable bathythermograph (XBT) line/float-launch site south of Portugal.

position within the Undercurrent, but these can be obtained from a small vessel using a portable expendable bathythermograph (XBT) system. A charter arrangement was deemed the best alternative, and we have engaged the 73-foot motor-sailing vessel, *Kialoa II,* for the six months of float deployments. (A former ocean racer, *Kialoa II* is owned and operated by Frank Robben, a retired University of California, Berkeley, mechanical engineering professor.) Each deployment trip takes about 24 hours to complete. The vessel leaves Vilamoura, a small town on the south coast of Portugal, at dawn, and reaches the first of the 20 XBT station sites by late morning. XBT stations are made approximately every 30 minutes while the vessel motors or sails along a transect crossing the Undercurrent . When the center of the current is located, two RAFOS floats are lowered by hand over the side, about 5 kilometers apart. The XBT stations are then continued to the offshore edge of the Undercurrent, and the vessel returns to Vilamoura in the early morning hours of the next day. Some cruises are being extended to three or four days to recover test floats or to make more extensive XBT surveys of the Undercurrent.

Most of our results will not be available until the middle of 1994, but some tantalizing observations have been made with a few floats deployed for 30-day test missions. The trajectory of one test float is shown at right superimposed on the bottom topography. This float drifted downstream in the Undercurrent for four days until it reached Cape St. Vincent, at the southwest corner of Portugal. It then started looping clockwise and moved away from the coast into deeper water. The float made eight complete loops before the end of its mission. This looping action, and the temperature record along the float trajectory, indicate that this float was caught in a new meddy—the first time the birth of a meddy has been documented.

When this experiment is complete, we will have many more trajectories illustrating how Mediterranean Water makes its way into the deep North Atlantic. We have already seen that Cape St. Vincent is a site of meddy formation. Other locations have been suggested, and our experiment will help to confirm or reject these sites of meddy formation. New sites may also be discovered. Once the major formation sites have been identified, the next step in understanding the meddy story will be to make detailed hydrographic surveys during the formation process to determine the mechanisms responsible for this remarkable phenomenon.



Trajectory of a RAFOS float deployed from Kialoa II *in July 1993. The dots indicate the float's daily position. The persistent clockwise looping of the float, starting at the southwest corner of Portugal, represents the first documented evidence of a new meddy's birth.*

This work is funded by the National Science Foundation.

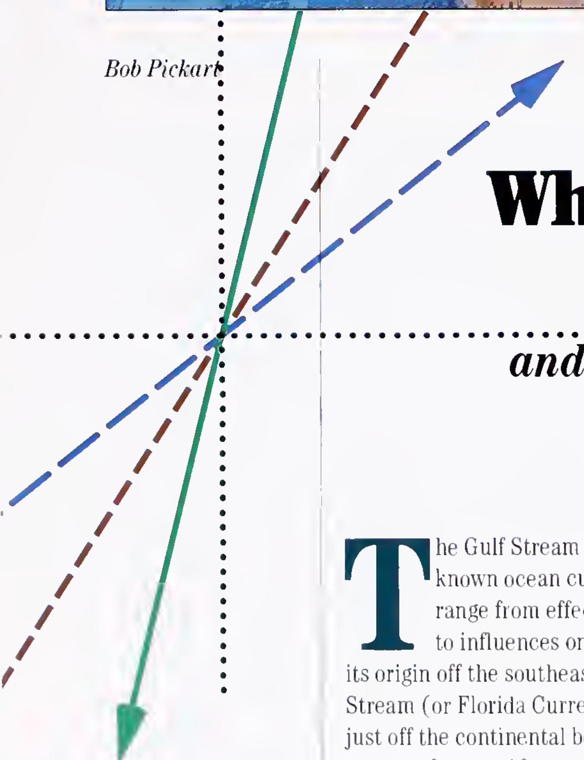
Amy Bower grew up in Rockport, Massachusetts, where her interest in science was nurtured by countless visits to Boston's Museum of Science, weather-watching, and high school math club. She discovered her sea legs (and the field of physical oceanography) as an undergraduate on R/V *Westward*, Sea Education Association's research schooner. Lessons learned on board *Westward* have helped her conduct science under sail on *Kialoa II*.

PHOTO COURTESY OF F. SOUSA

Amy Bower and João Martins (University of Lisbon) recover a test RAFOS float on the charter vessel Kialoa II *in July 1993.*

TOM KLEINDINST

Bob Pickart



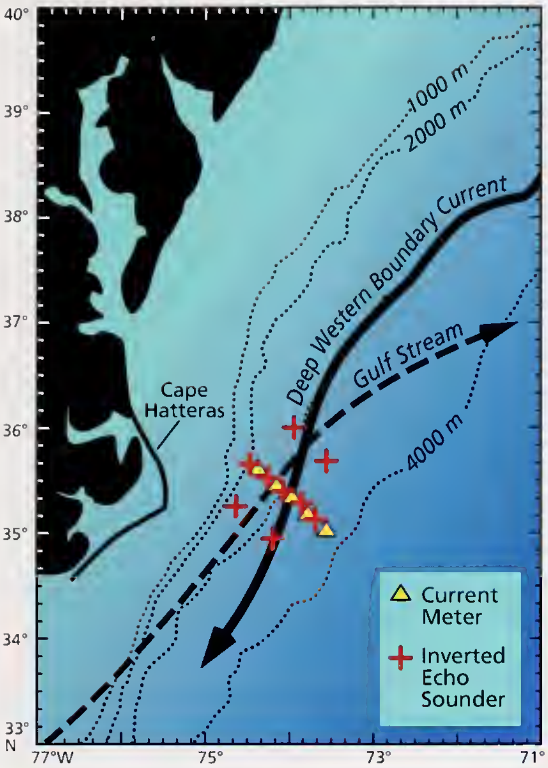
Where Currents Cross

Intersection of the Gulf Stream and the Deep Western Boundary Current

Robert S. Pickart
Associate Scientist, Physical Oceanography Department

The Gulf Stream is perhaps the most widely known ocean current because its impacts range from effects on trans-Atlantic shipping to influences on the European climate. Near its origin off the southeast coast of the US, the Gulf Stream (or Florida Current, as it is known there) flows just off the continental boundary in several hundred meters of water. After paralleling the boundary for roughly 1,000 kilometers the current abruptly turns offshore near Cape Hatteras, NC, and flows northeast toward Europe. Beyond Cape Hatteras the Gulf Stream extends to several thousand meters depth and meanders significantly, in marked contrast to the shallow, nearly straight Florida Current. The impact of this "separation" from the boundary is enormous, yet the precise reasons for the Gulf Stream separation (and that of other western boundary currents) remain unclear. The physics of the separation process is a topic of active research.

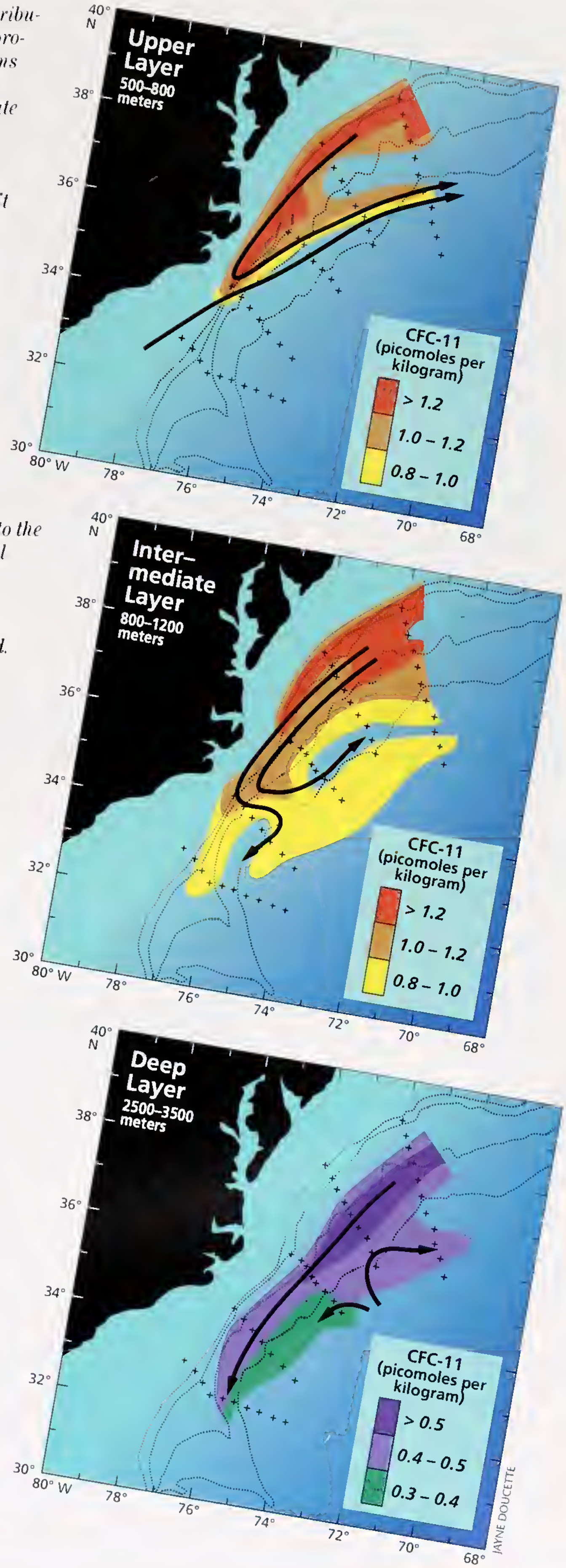
As the Gulf Stream turns offshore, into deeper water, it crosses the Deep Western Boundary Current (DWBC), which flows southwest toward the equator. The DWBC, carrying water recently formed at high latitudes, is the primary means for replenishing the deep waters of the vast ocean basins. Historically this crossing was thought to be of little consequence, with the upper-layer Gulf Stream simply passing above the deeper boundary current. However, new modeling



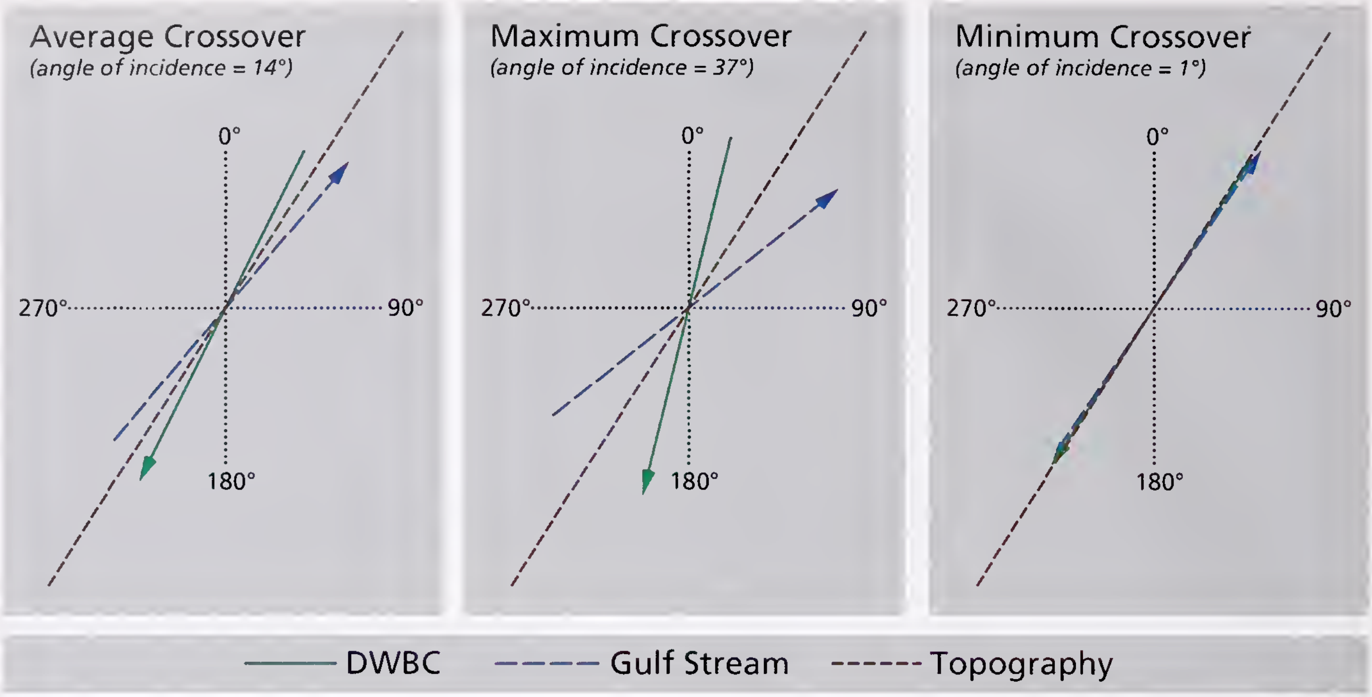
Study region of the Gulf Stream–Deep Western Boundary Current (DWBC) crossover, offshore of Cape Hatteras, NC. The historic paths of the Gulf Stream (from satellite observations) and DWBC (from water property measurements) are shown, along with locations of moored instruments.

results and observations reveal that the crossover has a profound impact on both currents, and may in fact contribute to the Gulf Stream separation mechanism itself. My fieldwork to address the Gulf Stream–DWBC interaction has included a shipboard survey of the crossover region in collaboration with a three-year moored instrument array (see figure above).

Since the upper portion of the DWBC extends to shallower depths than the separating Gulf Stream, one question concerns how this upper DWBC can survive its crossing and progress past the Gulf Stream. The shipboard survey measured density and various chemical properties of the water including chlorofluorocarbons (CFCs), which are used as refrigerants and aerosol propellants. The newly formed DWBC water is recognizable by its high CFC content, absorbed from the atmosphere while at the surface in high latitudes before sinking to form the DWBC. The lateral CFC distributions from the shipboard survey reveal that the upper part of the DWBC is actually sheared in half by the Gulf Stream. At shallow depths a tongue of high-CFC water is pulled offshore, implying that this portion of the DWBC turns with the Gulf Stream (top figure at right). This is confirmed by the trajectories of water parcels calculated from the density field. Below the separating Gulf Stream, the CFC distribution and trajectories are much different. Here a significant portion of the DWBC does progress past the Gulf Stream (although it bends



Lateral distributions of chlorofluorocarbons (CFCs) help reveal the fate of the Deep Western Boundary Current as it encounters the Gulf Stream. CFC maps at three different depths in the Deep Western Boundary Current are shown in relation to the water parcel trajectories calculated from the density field. Crosses denote shipboard-survey measurement sites, and dotted lines trace the underlying bathymetry.



Three years worth of moored measurements has revealed that the angle at which the Gulf Stream and Deep Western Boundary Current cross varies continually in time. The Deep Western Boundary Current responds to changes in Gulf Stream orientation with approximately a one-month delay.

seaward, apparently due to the Gulf Stream above it – middle figure, previous page). This "splitting" of the DWBC obviously impacts the transport of properties by the current to lower latitudes. The Gulf Stream's entrainment of newly formed water from the DWBC is an effective means of replenishing the interior basin. This entrainment also alters the dynamical structure of the Gulf Stream itself. Whether this contributes to the actual separation—as recent models suggest—remains to be sorted out.

The situation at depth is different still. The CFC map and water parcel trajectories near the 3,000-meter level show that the DWBC passes beneath the Gulf Stream with minimal difficulty and, as the bottom figure overleaf shows, there is also a significant inflow of water from offshore. This is not to say, however, that the Gulf Stream has no impact on the deepest portion of the DWBC. The three-year moored measurements simultaneously tracked the movement and orientation of the Gulf Stream and measured the flow of the near-bottom DWBC. These observations revealed that the path and transport of the DWBC are continually altered by fluctuations of the upper-layer Gulf Stream.

In particular, a change in the Gulf Stream's angle of separation causes a change in the trajectory of the DWBC (see the figure above), while an increase in Gulf Stream transport leads to a weakening of the DWBC. The effect of the Gulf Stream angle change is in accord with recent theory, though the reason for the DWBC weakening with increased Gulf Stream transport is still unclear.

While these recent measurements have improved our understanding of the complex Gulf Stream-DWBC crossover process, they have also led to more intriguing questions. For example, by what physics does the upper-layer Gulf Stream affect the deeper portions of the DWBC? The importance of these two boundary currents to the general circulation of the North Atlantic and the significant consequences of this crossing motivate continued investigation of their interaction. This will also shed light on similar crossovers in other areas.

This work was supported jointly by the National Science Foundation and the Office of Naval Research. It is summarized in an article entitled "How Does the Deep Western Boundary Current Cross the Gulf Stream?" (Journal of Physical Oceanography, *December 1993, pages 2602-2616).*

Robert Pickart was introduced to oceanography (and sea sickness) in college as a participant in WHOI's Summer Student Fellow program. Despite recent experiences, such as being knocked off his feet by large waves, he enjoys going to sea and the excitement of collecting new observations. His primary research interests are deep circulation and ventilation. His most challenging endeavor, however, is raising his four young children with his wife Anne.

TOM KLEINDINST

Phil Richardson hefts a RAFOS float aboard R/V Knorr.

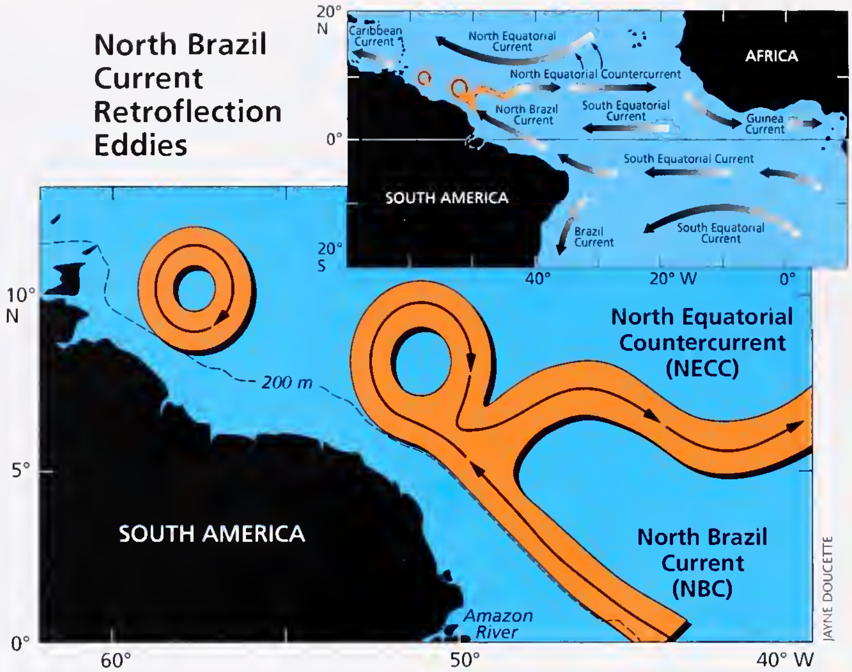
Giant Eddies of South Atlantic Water Invade the North

Disrupted Flow and Swirling Waters

Philip L. Richardson
Senior Scientist, Physical Oceanography Department

In the equatorial region of the Atlantic, the North Brazil Current follows the Brazilian coast northwestward before turning sharply to the right between 5°N and 10°N to cross the Atlantic as the North Equatorial Countercurrent. In 1990, satellite ocean color images were used to identify large, 400-kilometer-diameter, clockwise-rotating eddies that appeared to be separating from the North Brazil Current as it turned sharply to the east, much as warm-core Gulf Stream rings form from northward meanders. Because these eddies originate from retroflections or sharp changes in current direction, they are called North Brazil Current retroflection eddies. Satellite observations show them to be some of the largest eddies in the Atlantic and raise many questions about their numbers, life histories, and importance in the general circulation. Do these eddies provide a path for significant amounts of upper-layer South Atlantic water to travel up the coast? Do they transport water primarily in the near-surface layer or do they extend deeply into and below the thermocline? Do they drive recirculating flows in the underlying deep water as eddies are thought to do in the Gulf Stream system?

From 1989 to 1992 we were able to track six retroflection eddies for the first time using surface drifters and subsurface floats that were trapped in the eddies' closed circulation and looped in them for as long as five months (see lower figure on page 20). The



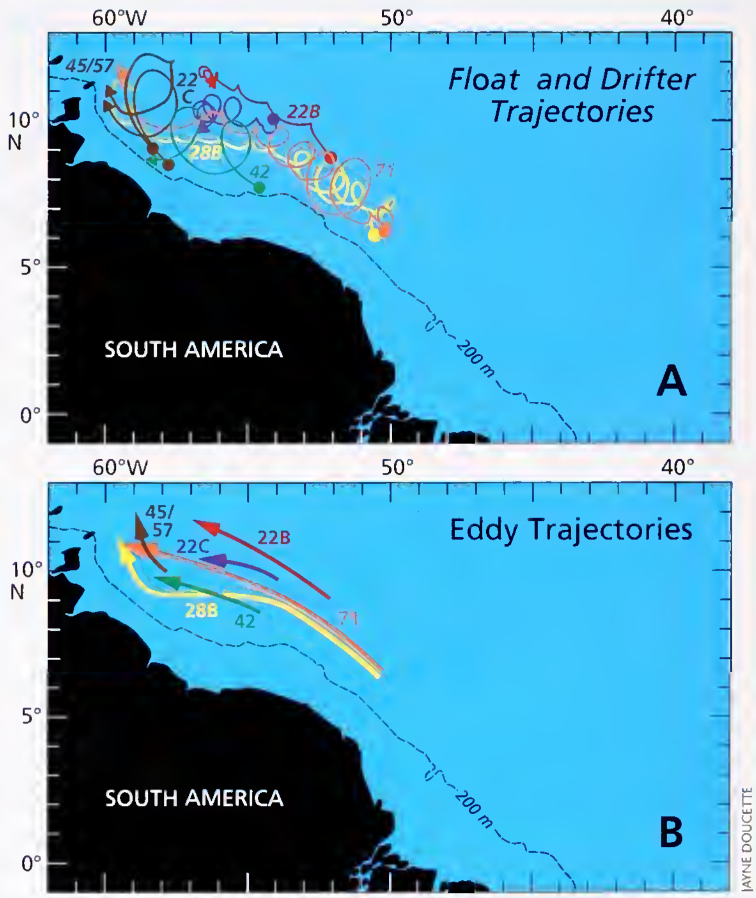
Retroflection eddies (orange) are water parcels that pinch off from the North Brazil Current and continue up the South American coast instead of remaining with the North Equatorial Countercurrent. Approximately three of these eddies form each year starting in July, when the North Brazil Current takes a sharp right turn, or retroflection. After an eddy pinches off near 8°N, the retroflection forms again farther south, near a latitude of 5°N to 6°N. Retroflection eddies are about 400 kilometers in overall diameter near the surface and drift northwestward at around 10 centimeters per second. They are thought to be responsible for carrying significant amounts of South Atlantic water northward into the Caribbean Current.

The inset schematic map shows the major tropical currents between July and September, when the North Brazil current retroflects and feeds into the eastward flowing North Equatorial Countercurrent. In contrast, from January through July the countercurrent disappears in the western tropics, westward velocities are observed in this area, and the North Brazil current continues up the coast as the Guyana Current.

looping trajectories were used to describe the number, movement, and characteristics of these eddies.

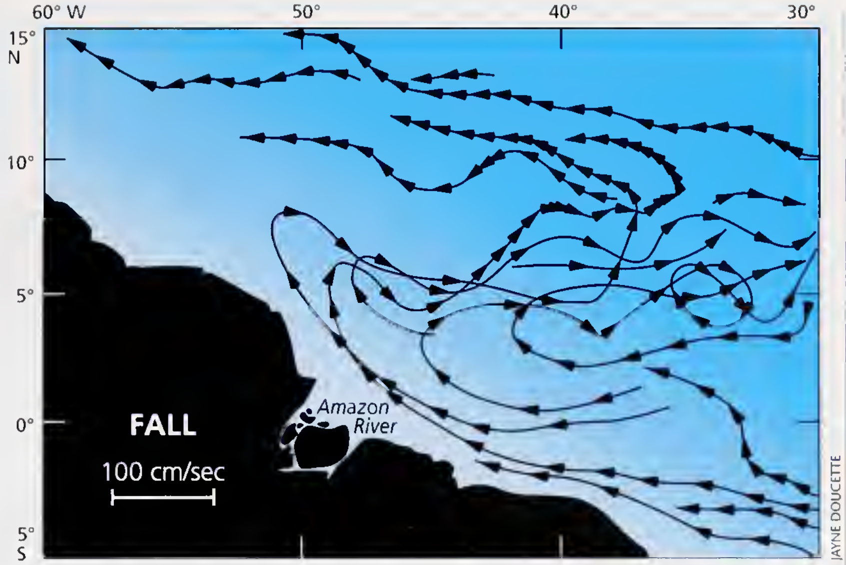
Looping surface trajectories had diameters up to 250 kilometers with swirl speeds as fast as 80 centimeters per second, dropping to diameters of 140 kilometers at 900 meters with swirl speeds of 35 centimeters per second. The deepest looper was at 1,200 meters with a maximum diameter of 100 kilometers and a swirl speed of 20 centimeters per second. The eddy shape, determined from the loop diameters, appears to be an inverted cone. The data suggest that at least three such eddies form each year from July to March. They move northwestward along the South American coast with a mean velocity of 10 centimeters per second, and seem to disintegrate when they encounter a 1,000-meter ridge between Barbados and Tobago. The water advected northward by the eddies probably then enters the Caribbean Current.

Retroflection eddies appear to carry a significant volume of South Atlantic water northward into the North Atlantic, short-circuiting the longer route around the gyre formed by the North Equatorial Countercurrent and the North Equatorial Current. Each eddy transports about a million cubic meters of water per second; three eddies per year account for as much as a quarter of the total northward transport in the upper limb of the thermohaline (temperature and salinity driven) circulation cell.



A) Composite of looping trajectories measured by surface drifters (42,45,57,71) and subsurface SOFAR floats (22B, 22C, 28B) in retroflection eddies from 1989 to 1992. Surface drifters' positions were recorded by orbiting satellites several times per day. Acoustic signals transmitted daily by the floats were recorded by a moored array of listening stations.
B) Inferred trajectories of six retroflection eddies. Three different eddies were observed during the period August 1989 to April 1990 (28B, 22B, 45/57).

Estimates place the total upper-layer current transport of water into the North Atlantic at about 13 million cubic meters per second. This upper-layer northward transport is balanced by the southward flow of cold North Atlantic Deep Water beneath the eddies. (See figures on pages 6 and 7.)



Surface-drifting buoy trajectories in the North Brazil Current retroflection during 1983 to 1985. All five available drifters retroflected during the months of July to December, implying that there was a complete break in the north-westward flow.

The discovery of numerous eddies translating up the coast helps explain a discrepancy between two earlier data sets, from drifting buoys and historical ship drifts, that show continuous flow up the coast to the Caribbean from January through June. From July through December, however, all available surface drifters (during 1983 to 1985) in the North Brazil Current retroflected into the countercurrent (see figure above). In these same months, ocean-color images also showed Amazon Water flowing around the retroflection into the countercurrent, implying a complete surface disruption of flow up the coast. These drifters and images contradict historical ship drifts, which show a continuous northwestward current there during July through December, with a branch feeding into the countercurrent. An explanation for this discrepancy involves retroflection eddies. The continuous current seen in ship-drift maps is probably an artifact of averaging many years of velocity measurements on the inshore side of the mean path of eddies, where eddy swirl velocity is northwestward. This is demonstrated by a map of surface-drifter velocity, including newer trajectories in retroflection eddies (see figure to right), that agrees with the earlier ship-drift data. The Guyana Current, if it exists during the months of July through December, is not a smoothly flowing current but instead consists primarily of a train of retroflection eddies.

It may seem surprising that we are just beginning to understand a major current system like this. Our ignorance has been caused partially by a lack of good in situ data sets and partially by the intermittent character of these powerful eddies and their rapid movement. Our knowledge about many subsurface currents is even more rudimentary, which suggests that we will find many more surprises in our ocean-circulation studies.

Funding for the work described was provided by the National Science Foundation. Recent scientific journal articles on the subject of this article include "Tracking Ocean Eddies" (Philip L. Richardson, American Scientist, *May-June 1993, pages 261-271) and "North Brazil Current Eddies" (P.L. Richardson, G.E. Hufford, R. Limeburner, and W.S. Brown,* Journal of Geophysical Research, *1994, Vol. 99, pages 5081-5093).*

Phil Richardson grew up on a cattle ranch in California where he spent long hours chasing cows. He ran away to sea and eventually earned a Ph.D. in oceanography from the University of Rhode Island. His early experience on the ranch has proven valuable in his recent efforts to follow floats and drifters in the oceans.

Mean velocity vectors calculated by grouping all available surface-drifter velocity measurements from 1983 to 1993 into 1°-by-1° bins. The newer data, which are similar to historical ship drifts, include trajectories in several retroflection eddies and show that on average the North Brazil Current runs continuously up the coast into the Guyana Current, with some flow peeling off and feeding into the countercurrent. The mean northwestward current is partly an artifact of averaging the clockwise rotating swirl velocity of several eddies as they drifted northwestward along the coast.


TOM KLEINDINST

Nelson Hogg with RAFOS floats that are being serviced in the laboratory.

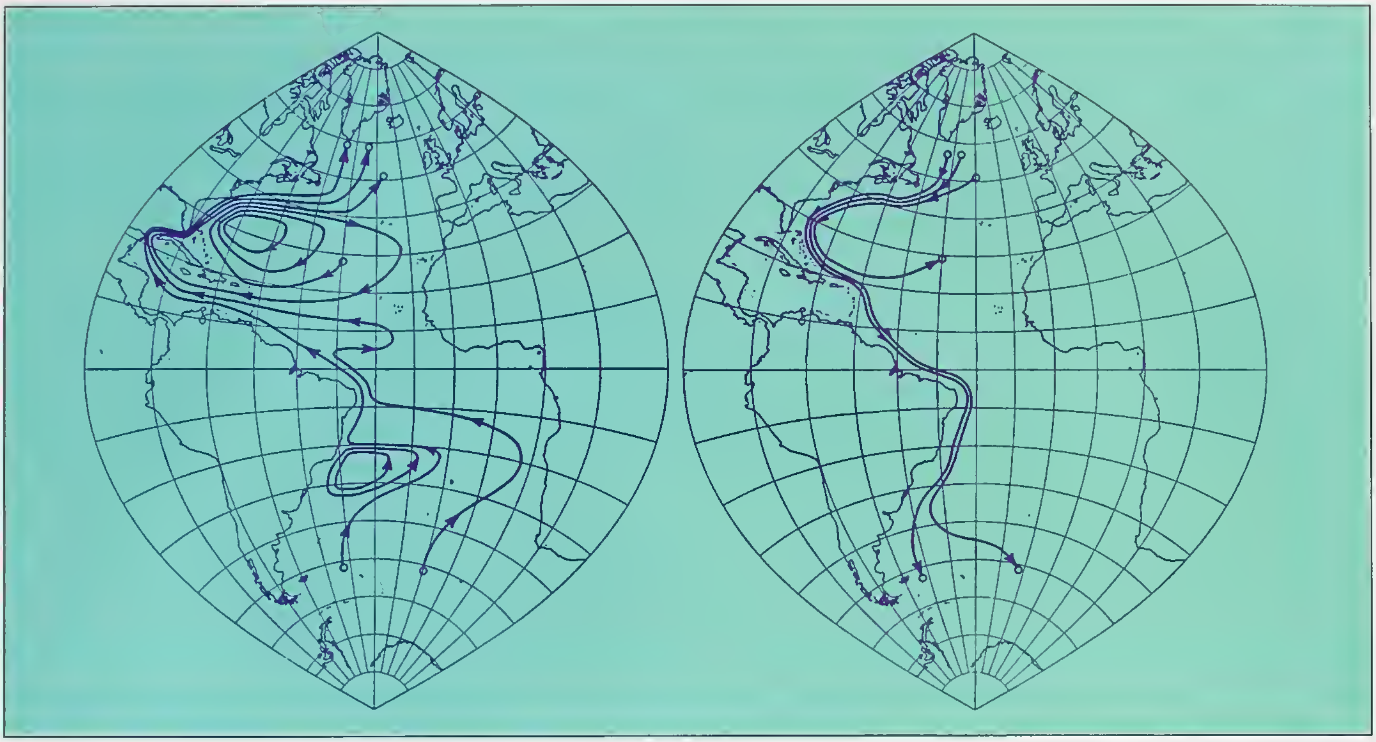
The Deep Basin Experiment

How Does The Water Flow in the Deep South Atlantic?

Nelson Hogg
Senior Scientist, Physical Oceanography Department

Fresh from his success at explaining why currents like the Gulf Stream are found along the western boundaries of all ocean basins, Henry Stommel proposed almost 40 years ago that there were similar features in the abyss. According to his scheme, these would be fed by water made dense in the polar regions during winter. This convective circulation would be completed by a slow bleed of water from the deep boundary currents into the ocean interior, and a broad rising through the ocean thermocline (a region of rapid decrease in temperature with depth) into the upper ocean where it would then be carried poleward (in, for example, the Gulf Stream) to complete the circuit.

Almost immediately, using conventional hydrography and a novel neutrally buoyant float that John Swallow (UK Institute of Ocean Sciences) had recently invented, Val Worthington (WHOI) and Swallow discovered the "Deep Western Boundary Current" part of the scheme on the Continental Rise south of Cape Cod. Then, with help from Stommel and others and using these same floats, Swallow set out to confirm the existence of the slow interior circulation that was an integral part of the scheme. Instead, they found that the deep ocean, away from the boundary, was dominated by a vigorous eddy field, much like the weather systems that dominate our day-to-day existence on land. With the ship-based technology then available, there was no hope of being

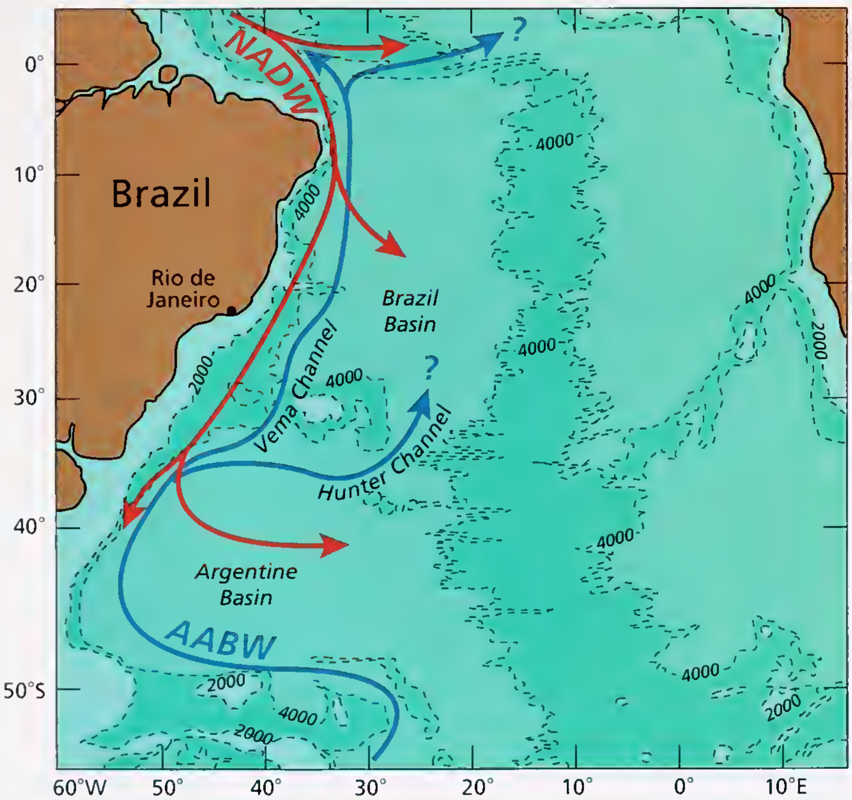


Upper (left) and lower (right) Atlantic Ocean circulation scheme proposed by Henry Stommel in 1957. Water is made dense by winter cooling, evaporation, and ice formation in the polar regions and then moves equatorward as narrow, relatively swift flows along the western margins. Water slowly leaks away into the interior and then upward across the thermocline to eventually return to the poles.

able to extract the very weak mean flow in the presence of so much noise from the eddies.

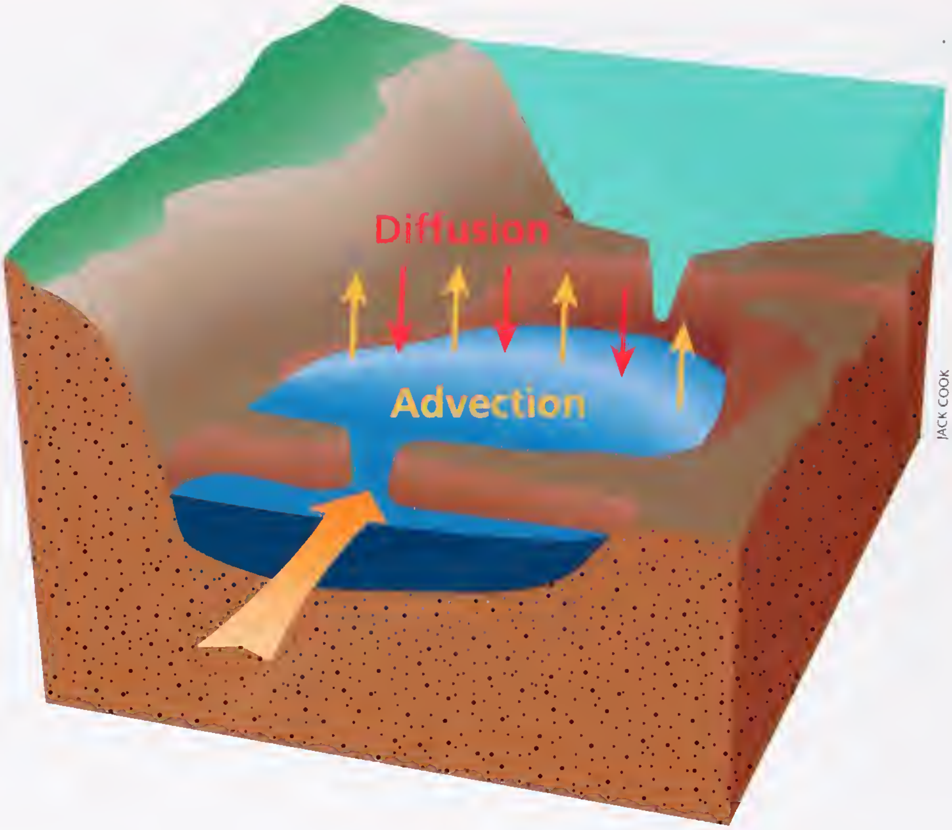
Advances in technology over the last four decades now make it possible to revisit this issue, and a group of US, German, French, and Brazilian scientists are engaged in an attempt to reveal the secrets of the deep circulation. We have centered our program on the Brazil Basin for several reasons: French and German oceanographers had already planned extensive hydrographic work in this region as their contributions to the World Ocean Circulation Experiment, previous work in the area suggests that the return circuit through the thermocline is surprisingly strong in this area, and the geometry of the Brazil Basin is relatively simple—there are just three major connecting passages to neighboring basins and the bottom and boundaries are smooth, except for the Mid-Atlantic ridge portion on the basin's eastern side.

The observational attack is multipronged. First we will complete an extensive network of "hydrographic lines," making temperature, salinity, and other measurements. The sampling strategy is designed to split the basin into a number of boxes. Using various conservation principles (such as for mass, momentum, heat, and salt), we hope to determine whether the rising process occurs



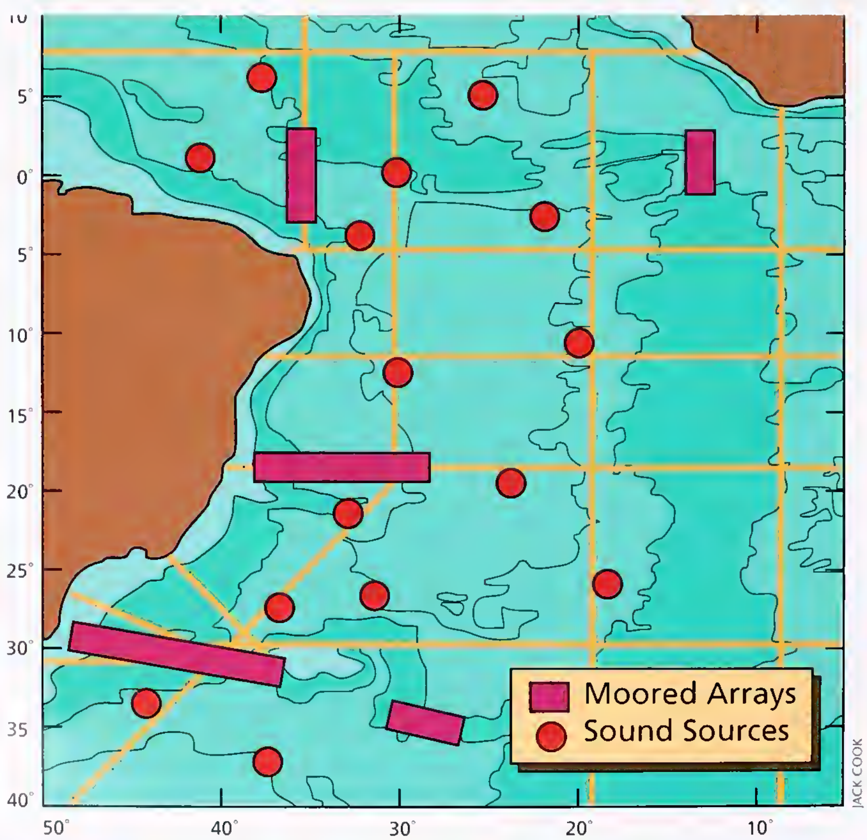
The bathymetry of the South Atlantic showing pathways for the flow of the two main deep water masses, North Atlantic Deep Water (NADW) and Antarctic Bottom Water (AABW).

A schematic illustration of how the deepest water entering the Brazil Basin from the south through the Vema Channel can conserve both mass and heat by rising and changing density. The water entering the basin below a certain temperature does not leave at that temperature, but instead rises and warms through downward diffusion of heat. This balance allows estimation of thermal diffusivity, a measure of the rate of mixing in the ocean.



uniformly across the basin, as in Stommel's visionary scheme, or perhaps is localized along the boundaries, as others have suggested. Current-meter moorings will also be deployed, mostly along the boundaries and within the deep connecting passages. Progress in electronics and mooring hardware now allows us to set these moorings for at least two years and anticipate a 90 percent data return. A similar array, moored across the Vema Channel some 15 years ago, was part of the inspiration for the Deep Basin Experiment: It showed that the deepest, or "bottom," water, was pouring into the Brazil Basin but had no exit other than to warm and rise.

Swallow's neutrally buoyant floats have evolved considerably over the last 40 years. We will be setting more than 200 floats, mostly of a variety known as RAFOS floats developed originally by Tom Rossby at the University of Rhode Island and now commercially produced in North Falmouth, MA. These floats listen for moored-acoustic-source signals that can travel great distances in the ocean, as much as 1,500 kilometers for our instruments and depths. Consequently, we need only nine moorings to ensure that a given



The Deep Basin Experiment field program. Filled circles locate acoustic sound sources that will track flocks of neutrally buoyant floats, rectangles indicate moored current-meter arrays, and lines show planned shipboard hydrographic surveys.

float will be able to hear at least two sound sources. Accurate clocks and knowledge of the speed of sound in water then allows triangulation on the float to determine its position to within about a kilometer. The miniaturization of electronics allows these instruments to be housed within what amount to large test tubes about 2 meters long. At the end of their two-to-three-year missions, they drop a weight and rise to the surface where they report their information to home base through a satellite link. With these flocks of long-lived floats, we anticipate now being able to fulfill John Swallow's dream of directly measuring the weak interior flow.

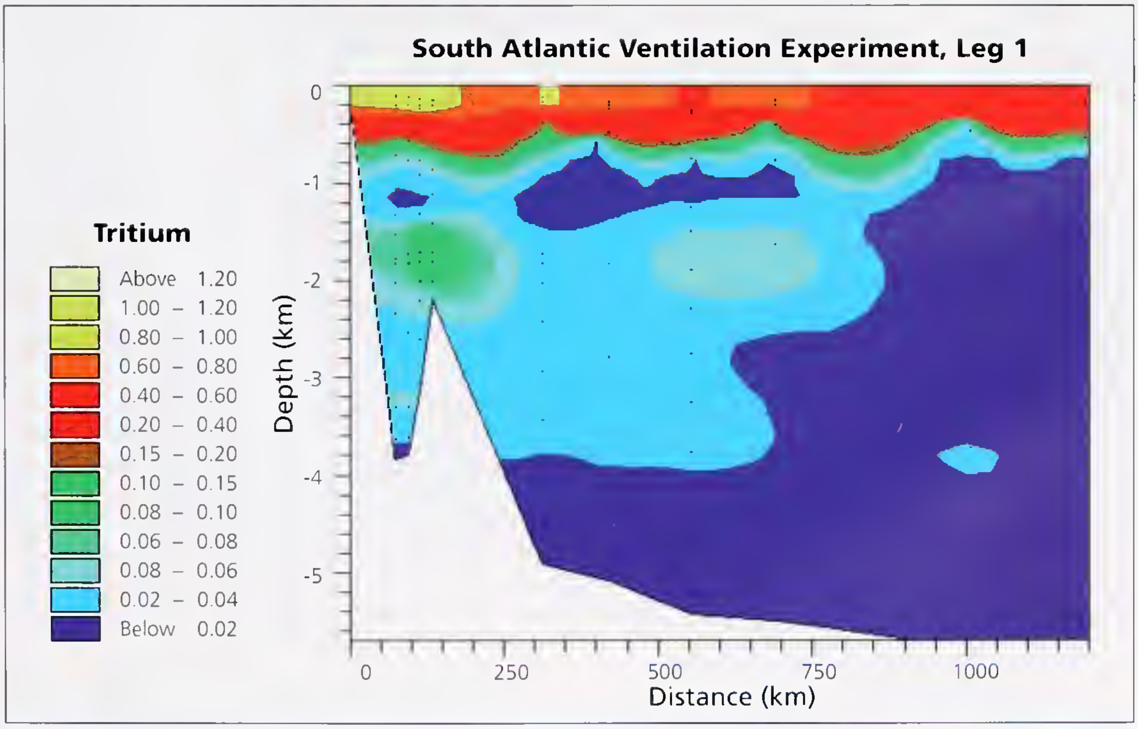
At least two observational techniques are available to us now that were unknown 40 years ago. Over that time, industry has been producing ever-increasing amounts of chemicals called chlorofluorocarbons for use as refrigerants and aerosol propellants, among other things. Chlorofluorocarbons disperse through the atmosphere and from there dissolve in the surface layers of the ocean and are incorporated in the sinking polar waters that are the sources for deep boundary currents. In addition, the 1950s hydrogen bomb tests introduced radioactive tracers into the amosphere and ultimately into the oceans, tritium being one measurable tracer that is taken up by the ocean. These become markers of the source water and allow us to estimate the time since that water was last in contact with the sea surface (figure below).

We have had no control over the input of these industrial and military pollutants to the oceans. Recently, however, WHOI Associate Scientist Jim Ledwell pioneered the use of a deliberately released, nontoxic chemical compound (known as sulfur hexafluoride) to directly infer vertical mixing rates in the ocean interior. Small but measurable amounts of this material are injected into the ocean over a small area at a specified depth. Over the next few months eddy processes stir the injected material both horizontally and vertically into a smooth distribution, much like stirring cream in a coffee cup. The rate at which the material spreads vertically is a direct measure of the process invoked by Stommel so long ago. Following very successful use of this technique in the thermocline of the eastern North Atlantic in 1992, Ledwell is now planning to perform a similar experiment in the depths of the Brazil Basin to answer the question of how rapidly processes away from the boundaries are able to carry the deep water back up to the thermocline on their return poleward journey.

The Deep Basin Experiment is in the early stages of field work, with a great deal of instrumentation installed in the Brazil Basin. Data collection will continue for several years, and then we can begin to attack the scientific issues that have been unanswered for the past 40 years.

US funding for the Deep Basin Experiment is provided by the National Science Foundation.

Nelson Hogg dreamt of being on warm, sunny beaches by the sea while growing up in northern Manitoba. It wasn't until he had a summer job during college at the Defense Research Establishment in Dartmouth, Nova Scotia, that he had that opportunity during an instrument-testing cruise to Bermuda. That was enough to convince him that oceanography had advantages over high-energy physics. For most of the time since then, he has been at WHOI.



A section showing tritium concentration along a line starting near 10°S on the Brazilian Coast and angling northeastward to cross the equator near 20°W at the Mid-Atlantic Ridge. The section ends at Africa.


TOM KLEINDINST

Mike Spall runs an ocean circulation model.

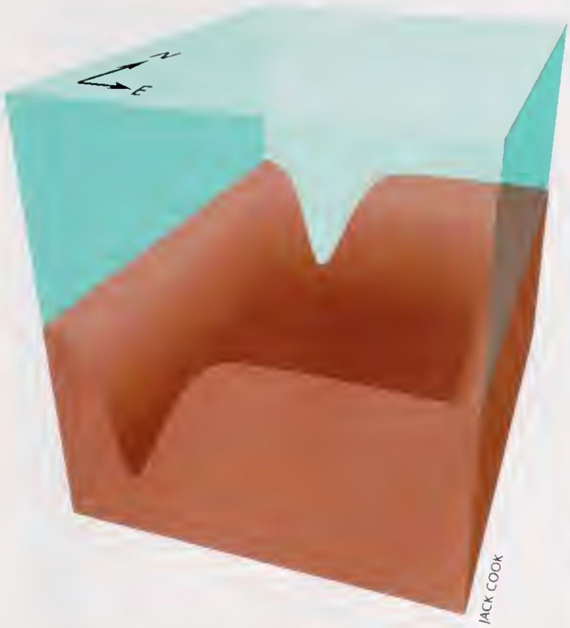
Wave-Induced Abyssal Recirculations

Turning This Way and That Way

Michael A. Spall
Associate Scientist, Physical Oceanography Department

It is generally believed that deep-ocean circulation plays a fundamental role in the global climate system. The abyssal circulation transports cold, fresh water formed at high latitudes toward the mid and low latitudes, where it upwells to maintain the main thermocline (a region of rapid decrease in temperature with depth) in the presence of downward heat diffusion. This is thought to be accomplished through a complex pattern of boundary currents and interior flows, although the dynamics, and even the paths, of these flows are not well understood. The traditional view of abyssal circulation stems from Henry Stommel's late 1950s and early 1960s theoretical work, which assumes that deep waters are formed in very small regions at high latitudes and uniformly upwell throughout the lower latitudes into the upper ocean. This simple model predicted that a series of deep western boundary currents in the world's ocean basins would carry the waters away from their regions of formation, and that the basin interiors would be characterized by very weak poleward flow.

However, recent basin-scale hydrographic measurements in the North Atlantic and in the Brazil Basin of the South Atlantic Ocean (the location of the World Ocean Circulation Deep Basin Experiment) indicate that strong flows are not confined to the western boundary regions. Instead, the abyssal ocean appears to contain significant large-scale recirculation gyres,



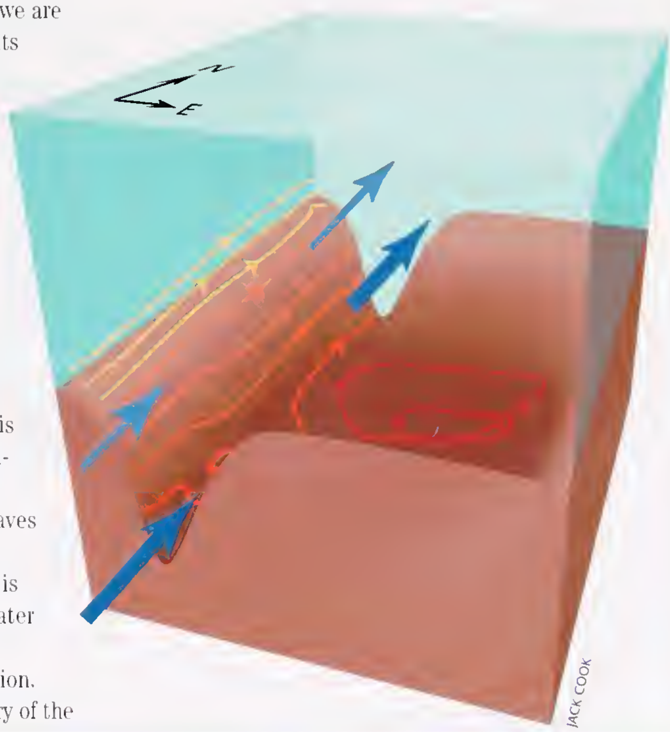
Schematic of the model domain representative of the Brazil Basin in the South Atlantic Ocean. The basin is bounded to the west by South America, to the east by the Mid-Atlantic Ridge, to the south by the Rio Grande Rise, and to the north by the Ceara Rise. Narrow channels allow Antarctic Bottom Water to flow into the basin from the south and out to the north, where it crosses the equator and enters the North Atlantic Ocean.

cross-basin flows, eastern boundary currents, and topographic waves (see Mike McCartney's article on page 5 for a discussion of the deep mean flows). The presence of these currents implies that the deep ocean is influenced by more complex physics than were included in the simple early models. Understanding the structure and forcing mechanisms of abyssal recirculation gyres, and their relation to the deep western boundary currents and upwelling, is essential if we are to fully understand deep-ocean circulation and its role in the global climate system.

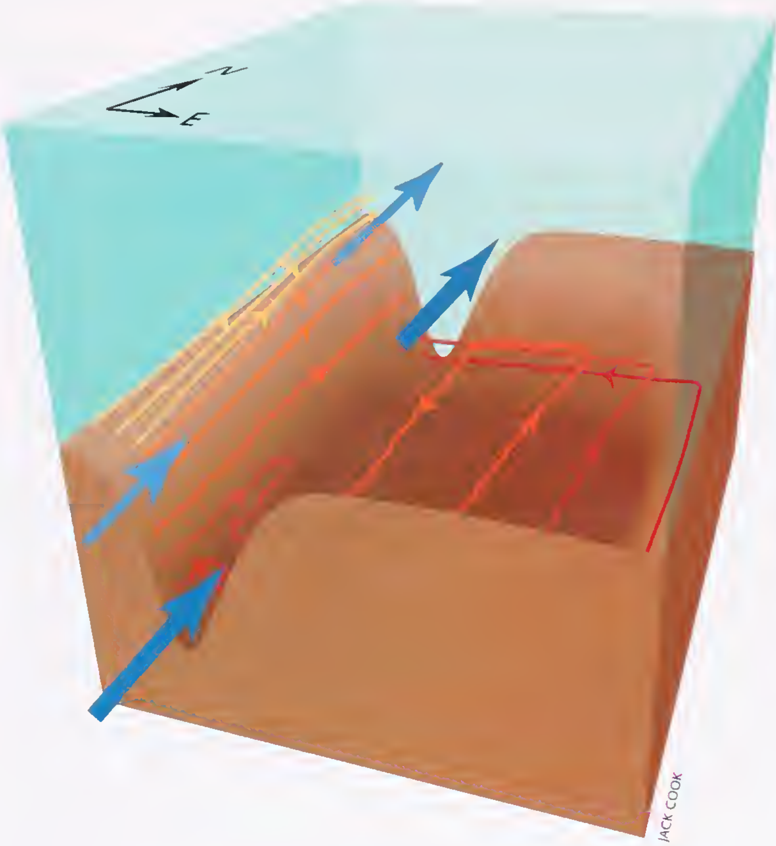
I have been using a numerical model to investigate some of the consequences of more complex physics on abyssal circulations. The model approximates the continuously stratified ocean as three constant-density layers. The two deeper layers represent the lower and upper Antarctic Bottom Water (Antarctic Bottom Water is a cold, fresh water mass that originates near Antarctica and flows into the Brazil Basin from the south); the shallowest layer represents the upper ocean. This system is well suited for studying abyssal circulation because it allows for steep and tall bottom topography, time-dependent motions, such as waves and eddies, and vertical mixing between water masses. The effect of mixing between the layers is paramaterized here as a uniform upwelling of water between the deeper two layers.

The figure above shows the model configuration. The domain is roughly patterned on the geometry of the Brazil Basin, with bottom topography approximating the deep bowl shape of the Brazil Basin between the South American coast and the Mid-Atlantic Ridge. The basin's southern and northern limits are partially blocked by ridges, representing the Rio Grande Rise in the south and the Ceara Rise to the north. The basin extends approximately 3,000 kilometers in the north-south direction and 2,000 kilometers east-west. We know that Antarctic Bottom Water is formed at very high latitudes in the southern oceans and spreads northward, passing through the Brazil Basin into the North Atlantic. We approximate this flow into the Brazil Basin by introducing a deep western boundary current of Antarctic Bottom Water through a channel at the southern boundary of the domain. The flow exits through a channel adjacent to the western boundary at the domain's northern limit. Transport within each outflow layer may be different from that at the inflow, allowing for overall warming of bottom waters.

We have conducted two sets of experiments, one with a steady and one with an unsteady deep western boundary current. We keep the physical configuration—stratification, topography, and flow strength—constant, and render the flow steady by increasing the current's drag against the bottom. This approach allows us to investigate the influence of time-dependent motion on the mean state under otherwise similar flow conditions and model physics. The schematic below shows the mean flow of Antarctic Bottom Water in the deep basin with a steady deep western boundary current. Consistent with traditional models of deep circulation driven by large-scale upwelling, the dominant circulation features are the northward flowing deep western boundary current and a large-scale cyclonic (clockwise in the Southern Hemisphere)



Schematic of the mean circulation of Antarctic Bottom Water from the model with a steady deep western boundary current. Colored lines indicate bottom water depth (yellow for shallow, red for deep) while arrows indicate flow direction. The bold blue arrows show where the water flows into and out of the basin. Most of the water is carried to the north over the sloping bottom along the western boundary in the deep western boundary current. There is a cyclonic (clockwise) recirculation with a depressed center in the basin interior.



Schematic of the mean circulation of Antarctic bottom Water from the model with an unsteady deep western boundary current. The deep western boundary current still flows to the north along the western boundary, but now the direction of flow in the basin interior is anticyclonic (counter-clockwise) with a raised center. The unsteady western boundary current entirely changes the mean-flow direction in the basin interior.

recirculation gyre in the basin interior. The flow indicated here is essentially void of any time-dependent motion.

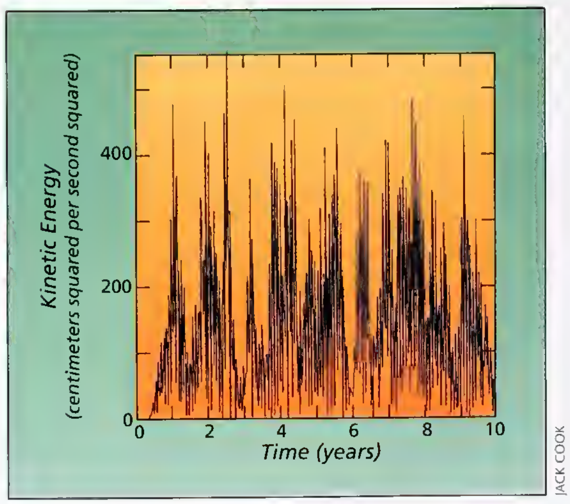
To investigate the influence of time-dependent motion, we repeat the calculation above with reduced bottom drag, which allows small perturbations in the mean flow to grow into large amplitude waves and eddies. The schematic above indicates that the mean deep western boundary current continues to flow to the north, but now the mean interior circulation is anticyclonic (counterclockwise), opposite to that found in the absence of time-dependent motions.

The nature of the variability near the western boundary is indicated in the figure at right by a kinetic-energy time series over the sloping bottom near the boundary. We find the passage of high-frequency events with velocities as fast as 15 to 20 centimeters per second about once each year. These currents are much faster than the mean speed of the deep western boundary current, which is approximately 3 to 4 centimeters per second. These energetic events are the signature of topographic Rossby waves that are generated by meandering of the deep western boundary current and that propagate downslope into the deep basin interior. These waves carry energy from the deep western boundary current into the basin interior and entirely change the direction of flow around the deep basin.

Recent observations of Antarctic Bottom Water circulation within the Brazil Basin indicate the presence of a basin-scale anticyclonic recirculation gyre with strength and distribution similar to that found in the model when waves are allowed to develop. Other aspects of the observations agree with the model circulation, including an eastward flow of lower and westward flow of upper Antarctic Bottom Water. A key to determining if the observed large-scale recirculation gyre is a result of wave propagation over the western slope, as predicted by the model, would be the presence of topographic waves with energy propagation into the basin interior. RAFOS floats and current meters recently deployed as part of the World Ocean Circulation Deep Basin Experiment should be helpful in testing this hypothesis. (See Nelson Hogg's article on page 22 for a discussion of the float experiment.)

This work is supported by the National Science Foundation and the German Bundesminister fur Forschung und Technologie. The main part of the research described here was carried out while Michael Spall was visiting the Institut fur Meereskunde in Kiel, Germany. A manuscript describing this work has been submitted for publication in the Journal of Marine Research.

Michael Spall became interested in oceanography while working on his Ph.D. in Applied Mathematics at Harvard University. He came to Woods Hole in 1990 after spending a postdoc at the National Center for Atmospheric Research in Boulder, Colorado. He enjoys spending time with his family, sailing, fishing, playing volleyball, and studying oceanography.



Kinetic energy over the sloping bottom near the western boundary. The high-frequency variability marks the passage of topographic waves that are generated in packets by the meandering deep western boundary current about once per year. Energy these waves carry into the basin interior causes the large scale recirculation gyres seen in the two previous figures to change directions.

"Most human history has not afforded men much chance to pursue their curiosity, except as a hobby of the rich or within the refuge of a monastery. We can count ourselves fortunate to live in a society and at a time when we are actually paid to explore the universe." – Henry Stommel, 1974

TOM KLEINDINST

Institution Director Robert Gagosian reads the citation for the Henry Stommel Medal in Oceanography before presenting the certificate to British oceanographer John Swallow. Elizabeth Stommel later presented the medal to Swallow. The medal likeness of Henry Stommel was sculpted by Judith Munk, a La Jolla, California artist and architect, and wife of Scripps oceanographer Walter Munk.

The Henry Stommel Medal in Oceanography

Established by the Trustees of the Woods Hole Oceanographic Institution

Awarded To

John Crossely Swallow, F.R.S.

For fundamental and enduring contributions to observing and understanding ocean processes, and in recognition of his exemplary seagoing oceanographic studies of North Atlantic, Mediterranean, and Indian Ocean circulation

February 9, 1994

The first Henry Stommel Medal in Oceanography was presented early this year to British oceanographer John Crossley Swallow, a long-time Stommel friend and colleague who is best known for his invention of the neutrally buoyant float (otherwise known as the "Swallow float") and its pioneering use in uncovering important elements of the ocean's general circulation. Stommel and Swallow shared many interests, but especially their desire to understand ocean circulation.

Stommel Medal Award Committee Chair Nelson Hogg described Swallow's capacity for hard work at sea as "legendary." In her remarks before presenting the medal named for her husband, Elizabeth Stommel said of Henry: "It was important, he said, to live with the ocean: to watch, to feel, to hear it, to confront it mindfully each day, to let it permeate one's life." The legendary combined work of Henry Stommel and John Swallow, at sea and ashore, have contributed mightily to the world's knowledge of ocean currents.

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